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DEEP THERMAL STREAM IN THE DAGESTAN TERRITORY

by A. S. Dzhamalova

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A. S. Dzhamalova[1]

ABSTRACT. The results of a study of the magnitudes and variations of the deep thermal flow and its radiogenic portion in sedimentary rock profiles in the Dagestan A.S.S.R. are presented in this book. The effect of the geostructural conditions on its distribution is evaluated. This book is useful for solving problems of the energetics of terrestrial processes and appraising geothermal resources.

PREFACE

The study of the deep thermal flow has important theoretical significance since information about it is absolutely essential in solving problems concerning the thermal history and thermal equilibrium of the Earth, deep temperature distribution, the energetics of geological processes, and a number of other problems. Study of the thermal flow permits exposure of the spatial differences in the intensity of the deep thermal field and opens the way for an evaluation of the role played by various factors in its formation. On the other hand, study of the thermal flow has great practical value in explaining the thermal regimen of specific portions of the Earth's crust and in determining perspectives for the utilization of subterranean heat. /5*

Considering the theoretical value of geothermal studies and the presence of considerable deep terrestrial heat resources in the USSR which could be utilized in the national economy, the value and the necessity of further universal development of works in this field are especially great. Among the most promising areas for the utilization of terrestrial heat is Dagestan.

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*Numbers in the margin indicate pagination in the foreign text.

Despite recent accomplishments in the field of heat flow spatial distribution studies, the number of its measurements on the continents is still far from adequate. Meanwhile, there are also no quantitative data concerning the significance of the various heat sources in the formation of the geothermal field. It was in this connection that the author attempted to study the deep thermal flow in differently structured portions of the Earth's crust on the basis of a specific area -- the Dagestan piedmont and plain -- and to make a quantitative evaluation of radiogenic heat generation in the sedimentary stratum. The study of this region is even more important because Dagestan is /6
of great interest as a promising region for practical utilization of terrestrial heat.

This work was completed over the period 1963-1967 under the direction of F. A. Makarenko, Doctor of Geological and Mineralogical Sciences, in the Laboratory of Geothermy and Hydrochemistry of Deep Earth Zone, Geological Institute of the Academy of Sciences of the USSR. On the basis of the results of this work, the author made experimental determinations of the thermal conductivity of sedimentary rocks in various areas of Dagestan (125 determinations) as well as measurements of the radioactive elements contained in the same rocks (100 determinations). The results of temperature measurements in oil wells were applied at the same time, which required special evaluation of the correlation of these data with the stationary heat field. In addition, the results of thermometric studies carried out in this region by other authors were studied. On the basis of these data, an analysis of the thermal field distribution is made in this work, as well as analysis of the role of radioactive decay within the sedimentary series in the geothermal regimen within the Earth's interior.

The experimental work and field studies were made in close association with the Dagestan Scientific Research Division for Energetics and the Administration of "Dagneft'". The Severo-Kavkazskoe (North Caucasus) Geological Administration, in the person of Zh. I. Shul'man, Director of the Geophysical Laboratory, was of great assistance in carrying out the experimental determinations of radioactivity of the rocks.

The author is deeply indebted to her supervisor, F. A. Makarenko, for constant advice and assistance.

Valuable counsel and comments were also received during the course of the study from Ye. A. Lyubimova, I. M. Kutasov, B. G. Polyak, V. A. Pokrovskiy, V. I. Kononov, Ya. B. Smirnov, and V. M. Sugrobov. The graphic material was prepared with the aid of N. I. Silin. To all of the persons named, the author expresses her most sincere gratitude.

CHAPTER I /7

A BRIEF REVIEW OF CURRENT IDEAS CONCERNING INTERNAL SOURCES OF TERRESTRIAL HEAT AND DEEP THERMAL FLOW

Thermal Effect of Radioactive Decay and of Other Heat Sources

Study of the thermal state of the Earth is closely associated with all of our geological concepts concerning the Earth and has a very long history. The first measurements of terrestrial temperatures indicating a universal increase in temperature with increased depth led to the hypothesis that this phenomenon is the result of the Earth's cooling down from its primeval molten state (Kelvin, 1864; Perry, 1895). But an estimate of the duration of the cooling down process was contradictory to the geological data concerning the age of the Earth. Numerous works exposed the nonconformity of this scheme of secular cooling with the actual thermal regimen of the Earth (King, 1893, Ingersoll, Zobel, 1913, and others). At the present time the origin of the Earth's heat is attributed principally to internal processes taking place in its depths. In addition, a significant role in the Earth's energetics is traced to cosmic influences (Kropotkin, Trapeznikov, 1963) and to the residual heat of formation of the planet.

Throughout the entire existence of the Earth enormous amounts of energy have been expended in mountain building, vulcanism, and other processes which resulted in the formation of the continents, oceans, and atmosphere. Solar heat serves as an energy source only for those processes taking place on the Earth's surface. All other energy comes from the depths of the Earth. The basic sources of this energy are the unexpended reserves of heat remaining after the formation of the planet, and the heat released by the decay of radioactive elements.

The majority of researchers attach a predominant importance to the /8
energy of radioactive transformations in the Earth (F. Birch, B. Gutenberg, R. Strutt, G. Jeffries, J. Jacobs, A. Holms, H. Urey, V. G. Khlopin, A. N. Tikhonov, Ye. A. Lyubimova, B. Yu. Levin, S. V. Mayeva and others). The majority of naturally occurring radioactive elements belong to the uranium,

Actinium, and thorium series which have, respectively, 20, 15, and 13 genetically related radioactive and stable isotopes. The half-life of these radioactive isotopes varies from millionths of a second to many billions of years. The transformation from one radioactive isotope to another, and then to a stable one, occurs by way of α- and β-decay; the γ-radiation of the uranium series is associated basically with the presence of Ra (B + C). Besides the radioactive elements of the uranium, actinium, and thorium series there are naturally occurring radioactive isotopes of potassium, calcium, rubidium, zirconium, indium, tin, tellurium, lanthanum, neodymium, samarium, lutecium, tungsten, rhenium, and bismuth. These are long-lived isotopes with half-lives exceeding 10^9 years; they are genetically unrelated to the other radioactive elements; β-decay or k-capture is characteristic for them.

When radioactive elements emit fast α- and β-particles and γ-rays which are absorbed by the surrounding medium, heat is liberated. The most accurate calculation of heat liberation is by means of the particle and wave energies. It has been established that all α-particles emitted by one element have one velocity; their masses are known, and the number of particles emitted by 1 g of the element in 1 sec is determined by direct tabulation. On the basis of these data it is possible to calculate the amount of energy released in α-decay. It varies in the different elements from 0.01 to 3.4 Mev (1 Mev = $= 0.039 \cdot 10^{-12}$ cal).

Computation of the rate of heat liberation by 1 g of material per year, U^{238} for example, is made in the following manner: in the decay of 1 atom of U^{238} to 1 atom of Pb^{206} plus 8 atoms of He^4 there is a release of 47.4 Mev, or $1.85 \cdot 10^{-12}$ cal. One gram of U^{238} contains $6.025 \cdot 10^{23}/238$ atoms; after 1 year the number of disintegrated atoms increases by a factor of $0.154 \cdot 10^{-9}$. Multiplying the number of disintegrations by the amount of heat liberated in each disintegration, we get 0.71 cal per year for 1 g U^{238}.

The release of a significant quantity of heat over the geologic time span is possible only when there is an abundance of isotopes in the Earth's crust which have a relatively large thermal decay effect and half-lives on the /9
order of the Earth's age. Isotopes which satisfy these two requirements are

U^{238}, U^{235}, Th^{232}, and K^{40}. All of them have half-lives on the order of 10^9 years or greater. The thermal effect of decay for these elements is given in Table 1. Numerous measurements of the thermal effect of decay of various radioactive elements, made by different authors at various times, show that for 1 g of rock the heat release value varies between $1 \cdot 10^{-6}$ and $6 \cdot 10^{-6}$ cal/year. Many short-lived radioactive elements, which are now obtained synthetically, may have existed at some time and possibly played an important role in the early period of the Earth's history. All isotopes with half-lives on the order of 10^8 years and less have by this time decayed to immeasureably small amounts.

TABLE 1. THERMAL EFFECT OF DECAY FOR RADIOACTIVE ELEMENTS (in cal/g·sec) ACCORDING TO THE DATA OF VARIOUS AUTHORS

Element	Bullard, 1954	Jacobs, 1956	Voytkevich, 1956	Urey, 1941
U^{238}	$2.34 \cdot 10^{-8}$	$2.33 \cdot 10^{-8}$	$2.33 \cdot 10^{-8}$	$2.22 \cdot 10^{-8}$
U^{235}		$14.9 \cdot 10^{-8}$		
U^{232}	$0.63 \cdot 10^{-8}$	$0.67 \cdot 10^{-8}$	$0.63 \cdot 10^{-8}$	$0.63 \cdot 10^{-8}$
K	$8.5 \cdot 10^{-13}$	$8.2 \cdot 10^{-13}$	$8.5 \cdot 10^{-13}$	$1.58 \cdot 10^{-13}$
K^{40}		$0.67 \cdot 10^{-8}$		

Element	Evans, Goodman 1942	Birch, 1953	Bullard, 1942
U^{238}	$2.33 \cdot 10^{-8}$	$2.30 \cdot 10^{-8}$	$2.28 \cdot 10^{-8}$
U^{235}			
U^{232}	$0.64 \cdot 10^{-8}$	$0.63 \cdot 10^{-8}$	$0.63 \cdot 10^{-8}$
K	$1.58 \cdot 10^{-13}$	$8.5 \cdot 10^{-13}$	$2.52 \cdot 10^{-13}$

There are certain difficulties associated with evaluating the heat re- /10
leased by radioactive sources as a function of depth and time because of the lack of information concerning the distribution of radioactive elements in the Earth's core.

The importance and necessity of radiologic investigations were demonstrated by V. I. Vernadskiy, in particular, who expressed ideas concerning the deep cross section of the planet's structure, permitting the distribution of radioactive energy to be traced to depths of 3.8 km below sea level over all the terrestrial surfaces. This was also demonstrated later by V. I. Baranov and A. S. Serdyukova (1959; Baranov, 1963); but investigations of this type are of episodic nature.

The equality of the flows on the continents and water areas, mentioned by many authors (E. Bullard, R. von Gertsen, Maxwell, Rivel, Nazan, V. Lee), led to the hypothesis that the continental rocks were differentiated from the underlying mantle and that, as a result of this differentiation, U, Th, and K were concentrated in the continental crust while beneath the oceans they remained distributed over a great range of depths (Bullard, 1964). On the basis of accumulated radiological data, Ye. A. Lyubimova (1964), considers U, Th, and K to be contained in effective quantities in not only the granitic and basaltic layers of the Earth's crust, but also significantly deeper, in the mantle, assuming at the same time that the radioactive geosphere diminishes with depth. Data concerning the integral flow are presented in Table 2, and in Table 3 are given the results of investigations of the total radioactive decay energy, in each instance for the period of the Earth's existence according to the data of various authors. Comparison of these tables indicates that the heat generated by radioactive elements during the Earth's existence is quite adequate to cover the total heat loss resulting from molecular heat conductivity. Determinations of the radioactivity of rocks indicated, too, that the current heat loss of the Earth may be compensated in the form of heat generation in the layer extending to a few tens of kilometers in depth, providing its radioactivity is equal to that of the normal surface rocks.

Radioactive elements are present in the lithosphere in the composition of minerals as well as in the absorbed state. More than 200 minerals have been identified in which radioactive uranium, thorium, radium, or potassium /11
are part of their structure. But the radioactive elements compose a very insignificant part of the total lithosphere. Rocks of different compositions

are characterized by different average contents of the radioactive elements (Table 4).

TABLE 2. INTEGRAL HEAT FLOW FOR THE PERIOD OF THE EARTH'S EXISTENCE (Ye. A. Lyubimova, 1966a)

Model	Earth's age, $8 \cdot 10^9$ years	Radiation constant	Content 10^{-3} g/g	Heat loss during period of Earth's existence (Q), 10^{38} erg	Author
Considering heat loss only through heat conductivity	4	0		0.112	Jacobs 1956
Considering more intensive heat transfer in the Earth's interior in the form of radiation components with radiation constant ε = 10, 100, 1,000.	4	10		0.125	Allan 1954
Considering redistribution of the radioactive elements from a homogenous to a continental structure	4.5	10	1.0	0.623	Lyubimova 1958
Considering uninterrupted redistribution of the sources	4.5	200 40 40	5.2 2.6 5.2	0.216 0.253 0.302	Levin, Mayeva, 1954
Uniform radioactivity in the mantle	4.5	1000	5.5	0.176 0.057	MacDonald 1964
Continental structure	4.5	1000	5.5 1.1	0.815 0.162	"
Oceanic structure	4.5	1000	5.5 1.1	0.742 0.143	"

According to A. P. Vinogradov's tentative estimate (1956), the lithosphere to a depth of 16 km contains (wt %): U^{235}, $2.1 \cdot 10^{-6}$; U^{238}, $3 \cdot 10^{-4}$; Th^{232}, $8 \cdot 10^{-4}$; Ra^{226}, $1 \cdot 10^{-10}$; Ra^{231}, $1 \cdot 10^{-10}$; Ac^{227}, $6 \cdot 10^{-14}$. I. D. Dergunov (1959) figures the distribution of the radioactive elements in the rocks to be 70% in the acidic rocks, 20% in the basic, and 10% in the ultrabasic. /12

TABLE 3. TOTAL ENERGY* RADIATED BY THE LONG-LIVED ISOTOPES DURING THE EXISTENCE OF THE EARTH (E. A. Lyubimova, 1966)

Author	Earth's age $8 \cdot 10^9$ yrs.	Energy, 10^{38} erg.	Proposed area of Concentration of Radioactivity
Vinogradov, 1960	4.5	1.1-1.5	Crust and mantle
Birch, 1961	4.5	0.6	400 km of upper mantle
Urey, 1962	4.5	1.2	Earth's mantle
Lyubimova, 1958	4.0	1.6	Earth as a whole
	4.5	2.0	Earth as a whole
	5.0	2.8	Earth as a whole
MacDonald, 1959-1964	4.5	1.4	Upper mantle
Levin, Mayeva, 1960	4.5	1.2-1.5	Earth as a whole
	6.0	3.0	Earth as a whole
Voytkevich, 1961	5.0	1.9	Earth as a whole
	6.0	3.7	Earth as a whole

*Calculated by the formula $H=\frac{1}{c\varphi_0}\int_0^\tau d\tau \int_V \sum_i H_i e^{-\lambda_i \tau} dV$, where λ_i is the constants of decay and content of the i-th radioactive element at the initial moment; c is the thermal conductivity; ϕ is the density, V is the Earth's volume; τ is the Earth's age.

The amount of heat liberated by any element in a given layer of the Earth per unit of time is determined by the content of that element (in grams) in 1 g of each of the rocks comprising that layer, by the amount of heat liberated in 1 sec during the decay of 1 g of the given element, and by the relative content of the different kinds of rock in the given layer. In order to relate the mass with the volume it is necessary, of course, to know the density of the various rocks.

With respect to the hypothesis that the basic mass of radioactive elements is concentrated in the upper mantle of the Earth, the role of radiogenic heat in the formation and development of the terrestrial crust, and especially the upper portion of it, must be enormous. /13

The investigations by R. J. Strutt at the beginning of the 20th Century indicated that heat formed by the decay of uranium, thorium, and potassium contained in the Earth's crust may produce the heat flow observed at the surface of the Earth. Calculations by V. G. Khlopin (1937) seemed to be new confirmation that radioactive heat in the crust, which was assumed to be 91 km in thickness, produced heat flow at the surface at the rate of 60 cal/cm^2 per year. In these calculations Khlopin assumed the granite layer to be 20 km in thickness, the basalt 40 km, and the peridotite 31 km, and assumed that the heat was adequate to compensate, in the form of atomic decay, for the planet's entire heat loss through radiation. G. V. Voytkevich (1961) and I. D. Dergunov (1959) note that Strutt and Khlopin proceeded from an overestimated content of radioactive substances in the crust, but introduction of the necessary corrections into their calculations does not change the resulting conclusions. Thus the majority of scholars today believes that the basic source of the heat, which is the motive force of all the processes taking place in the upper layer of the Earth's crust during the course of geologic time, is the decay of radioactive elements contained in the crust.

There is possibly a contribution to the Earth's energy balance from other sources besides the natural radioactivity of the long-lived isotopes. We shall examine specific cases.

The thermal effect of the decay of short-lived isotopes -- Al^{26}, Be^{10}, Cl^{36}, Fe^{60}, Np^{237} -- having half-lives of 10^6-10^7 years, which is considerably less than the age of the Earth, was examined by Ye. A. Lyubimova (1962), G. MacDonald (1959), and J. Jacobs (1961). According to the data of these investigators it provides only the initial warm-up of the inner core of the Earth and embryonic planets.

The unequal temperature distribution and the heterogeneity of the physical properties in the Earth's upper mantle are definite causes of thermoelastic stresses (Lyubimova, Magnitzkiy, 1964). The order of magnitude of the thermoelastic energy at a depth of 10 km is comparable to that of the seismic energy, and at a depth of 100 km even exceeds it.

The full gravitational energy, U, released during the formation of the dense core and less dense mantle, is evaluated for the mass M of constant density by the formula /15

$$U = -\frac{1}{2}\int_M W dm = -\frac{1}{2}\int_V W_p dv,$$

where M is the mass; V is the volume, and W is the energy of the individual element (of volume or mass). The energetic effect of gravitational differentiation and the redistribution of the terrestrial masses under the influence of cosmic factors, according to contemporary theories (Kropotkin, Trapeznikov, 1963; Lyubimova, 1959; Lyustikh, 1951; Safronov, 1954; Fesenkov, 1957; Beck, 1962; Benfield, 1950; Ferkhugen, 1958, 1961, and others), is commensurate with the thermal yield from the radioactive decay of elements distributed uniformly in the mantle and core in concentrations close to that of chondrite. The potential gravitational energy of the contemporary stratified Earth is $2.5 \cdot 10^{39}$ ergs, according to A. E. Beck (cited in Ye. A. Lyubimova, 1966).

The energetic effect of the Earth's rotational deceleration due to tidal friction over the period of the Earth's existence is $3.6 \cdot 10^{37}$ ergs. This energy may be essential for formation of fusions in the narrow layer, since the release of tidal friction energy is probably concentrated in the areas of reduced viscosity.

It is difficult to evaluate accurately the energy of geochemical reactions and phase transitions; processes may occur with the release as well as with the accumulation of heat.

The thermal effect of zonal fusion, capable of producing repeated fluctuations of the heat flow, is pointed out by Vinogradov (1959), Magnitskiy (1965), and Lyubimova (1966a).

The effects of spontaneous nuclear fission, cosmic radiation, and radioactive transformations of short-lived elements are considered insignificant (Magnitskiy, 1965).

TABLE 4. AVERAGE CONTENT OF RADIOACTIVE ELEMENTS IN ROCKS (in g/g)

Type of rock	A. P. Vinogradov (1956)			V. N. Kobranova (1962)				G. Tilton and G. Reed (1963)			
	$U \cdot 10^{-6}$	$Th \cdot 10^{-6}$	K	$Ra \cdot 10^{-12}$	$U \cdot 10^{-6}$	$Th \cdot 10^{-6}$	K	$U \cdot 10^{-6}$	$K \cdot 10^{-6}$	$K/U \cdot 10^{-6}$	Total heat gener. erg/year per 1 g
Igneous											
Acidic	3.5	18.0	0.033	1.4	4.0	13.0	0.26				
granite								4.0	35,000	$8.7 \cdot 10^3$	185
Intermediate	1.8	7.8	0.023	0.5	1.4	4.4	0.02	2.0	18,000	$9.0 \cdot 10^3$	143
Basic	0.8	3.0	0.008	0.4	1.2	4.0	0.014				
basalt								0.8	7,500	$9.4 \cdot 10^3$	58
eclogite								0.043	530	$1.2 \cdot 10^4$	
Ultrabasic	0.03	6.0	0.005	0.2	0.7	2.0	0.04				
peridotite								0.006	10	$1 \cdot 10^4$	0.38
dunite								0.001	10	$1 \cdot 10^4$	0.08
Sedimentary											
clays				1.3	4.3	13	--				
sandstones				0-1.5	up to 4.0	--	--				
limestones				0.5	1.5	0.5	--				
dolomites				0.11	0.3	--	0.26				
Chondritic meteorites								0.011	830	$7.5 \cdot 10^4$	1.56

Finally, pointing out that the parity of the heat flow on the continents and and the oceans is difficult to explain proceeding from a model of heat generation by internal radioactive sources, J. Isaacs and H. Bradner (1964) propose a model in which a flow of neutrinos, arriving on Earth from outer space, are considered to be the cause of heat flow. The authors estimate the flow of neutrinos arriving from the sun, the magnitude of the heat generation from scattering and electromagnetic interaction, as well as from nuclear reactions resulting from the capture of neutrinos by the matter of the Earth. It is also noted that the neutrino stream from the sun is insufficient /16
to explain the magnitude of the heat flow; the considerable stream of neutrinos from outer space must be taken into consideration and the importance of weak nuclear interactions must be recognized.

An evaluation of the energetic effect of various sources is introduced below (Ye. A. Lyubimova, 1966a). The relative importance of all these processes changes with time and in the different geospheres.

Type of Energy	Magnitude, 10^{38} ergs
Potential gravitational energy	25
Elastic energy	2
Energy from radioactive decay of U and K	0.6-2.0
Energy of gravitational differentiation.	1.5
Thermal content of the Earth's mass together with the temperature of fusion.	3.2
Energy of tidal friction	0.36
Heat loss through thermal conductivity	0.1-0.8

Our ideas concerning the thermal state of the Earth will, without doubt, be changed considerably, depending on assumptions about the genesis of our planet, the amount and distribution of radioactive elements, and the evaluation of the thermal effect of the various processes taking place in its interior. Thus the calculations of G. MacDonald (1964a) show that it is possible to construct a model of the Earth in which the radioactive composition differs from that of the chondritic meteorites, and which presents a surface flow and a distribution of temperature with depth, which does not contradict the observations.

E. Bullard (1964) writes that the thermal state of the Earth is the subject of much uncertainty and that arguments, stemming from it cannot be reliably used to determine what does and does not take place. The only means, therefore, of obtaining objective information at this time concerning the thermal regimen of the abyssal zones of the Earth is analysis of the actually observed phenomena in the subsurface layers, one of which is the thermal flow from the interior.

The Relation of Deep Thermal Flow to Geologic Structure /17

The thermal flow values in different places are rather strongly differentiated, from fractions up to 10 $\mu cal/cm^2 \cdot sec$. Attempts to determine its arithmetic mean value have been made at various times. Values obtained from an ever increasing number of observations have been proposed as arithmetic means: 1.3 ± 0.1 (Birch, Sherer, Spicer, 1949); 1.2 ± 0.6 (Birch, 1954), 1.23 (Bullard, 1954), etc. The value of 1.5 ± 10% is indicated as the most reliable world average (Lee, MacDonald, 1963). Applying different mathematical methods these authors determined the possible range of averages as 1.63-1.65 $\mu cal/cm^2 \cdot sec$.

The primary insufficiency of all these works was the application of heterogenous data. At the same time, general agreement of the pattern of thermal flow magnitudes with the geotectonic scheme had been proposed long /18 before (Kropotkin, 1948; Birch, 1954; and others). The first confirmation of this was the establishment of uniformly low values for the thermal flow on the Precambrian shields, 0.9-1.1 $\mu cal/cm^2 \cdot sec$ (Kraskovskiy, 1961; Lee, 1963). High thermal flow values, up to 2 $\mu cal/cm^2 \cdot sec$ and more, in recent folded mountain structures then attracted attention (Lee, 1963; and others), and particularly in regions of Cenozoic vulcanism (Uyeda, Horai, 1964; Bodvarsson, 1954; and others). As a result researchers turned to the analysis of geologically similar areas. Lee and Uyeda, applying methods of mathematical statistics to the analysis of 131 terrestrial determinations, obtained the data summarized in Table 5. These authors again indicated a value of 1.5 as the general worldwide average. The statistical calculations of B. G. Polyak and Ya. B. Smirnov (1966, 1968) analyzing the thermal flow in the various tectonic regions of the continents come closest to satisfying the requirements of uniformity and independence of all the data processed in the contemporary geologic-geophysical study of the Earth (Table 6). It can be seen from these calculations that the weighted average values of the thermal flow are, within an accuracy of ± 10%, 1.15, 1.19, and 1.18 $\mu cal/cm^2 \cdot sec$ for the land area, oceans, and Earth as a whole, respectively (Smirnov, 1966).

TABLE 5. THERMAL FLOW STATISTICS FOR THE MAJORITY OF DRY GEOLOGICAL STRUCTURES (Lee, Uyeda, 1965).

Geological Structure	Number of values	Arithmetic mean value	Standard deviation	Mean error	Average model value
Precambrian shields.............	26	0.92	0.17	0.03	0.9
Postcambrian unfolded regions.............	23	1.54	0.38	0.08	1.3
Postcambrian folded regions*............	68	1.48	0.56	0.07	1.1
Paleozoic........	21	1.23	0.40	0.09	1.1
Mesozoic.........	19	1.92	0.49	0.11	1.9-2.1
Cenozoic Vulcanism regions.............	11	2.16	0.46	0.14	2.1

*Except for Cenozoic volcanic regions.

The thermal flow is a physical quantity which is a function not only of the tectonic structure, which is expressed in its areal variations, but which, according to its nature and the contemporary concepts concerning sources of heat within the Earth, must be a function of various processes whose role is not constant with respect to depth (ground water movement, the decay of radioactive elements, the presence of local exo- and endothermic processes, intrusive penetrations, etc.), a factor which is perhaps expressed in the regular vertical variations in the magnitude of the thermal flow.

Determination of the quantity of thermal flow at the different test points at various depths is therefore to some degree arbitrary. This condition would have to be considered objectively in systemization of the data already obtained. But the magnitude of error introduced as a result of contemporary disregard of these tendencies is not clear.

The amount of all the direct deep heat loss is not accounted for by conductive heat flow alone. To the heat losses of the Earth through thermal conductivity must be added those losses which occur by other means. Such phenomena as orogeny, folding, metamorphism, and magmatism require great expenditures of energy. For example, according to P. N. Kropotkin's calculations (1948) up to 10^{27} erg/year are expended on mountain building in the present epoch. From 75 to 120 cal are consumed in the metamorphism of one gram of mass of rock (Fife, Turner, Ferkhugen, 1962), and 2-3 cal in elastic deformations (Goguel, 1948). Volcanic activity on the Earth in the present epoch is accompanied by an expenditure of approximately 10^{11} cal/sec (Polyak, 1966). /20

In view of the spatial coincidence of intense manifestations of these processes with established zones of high thermal flow it can be concluded that the magnitude of the thermal flow characterizes the energetic regimen of a given portion of the Earth's crust. Very significant in this connection is Bullard's statement (1964) that the Earth's tectonic processes are in some sense a thermal machine, and that in the study of thermal flow we are investigating the motive power of geologic changes.

It should also be kept in mind, that part of the deep thermal "flow" is truncated by waters circulating in the sedimentary layer of the Earth. Not once is this important role of the groundwaters indicated by V. I. Vernadskiy, E. N. Lyustikh, F. A. Makarenko, A. M. Ovchinnikov, N. A. Ogil'vi, G. M. Sukharev, and other researchers. Several quantitative solutions appraising the value of the convective heat conductance in the lithosphere have already been achieved (N. A. Ogil'vi, N. M. Kruglikov, N. M. Frolov, and others). Investigations in this direction are continued. At each point the total clear losses of deep heat q_{true} are equal to the algebraic sum of the conductive q_{cond} and convective q_{conv} heat losses. The magnitude of q_{conv} depends on the direction and rate of the water movement, and at one and the same geographical point the relationship between the convective and conductive components may vary along the vertical, depending on the hydrogeological peculiarities of the profile, while the amount of total heat loss remains the same (Polyak, 1966). At the same time this author emphasizes that determinations of the conductive component of the thermal flow are made at various depths and in different geological-hydrogeological structures, which /21 in his opinion, might, in themselves, lead to different partial values for q_{cond}.

It should be added, that in comparison of the values of the conductive component of the thermal flow at different points it is necessary to set forth stringent requirements for the geological-hydrogeological uniformity of the sections being compared. Comparison of incomparable values may lead to conclusions which give a false picture of the temperature regimen in the regions in question. For example, investigations of the thermal flow in the area of Cambridge, conducted by Chadwick (1956), yielded a value of 1.28 ± 0.12 $\mu cal/cm^2 \cdot sec$ in the Paleozoic folded bedrock, while for the upper part of the profile of the nearby platform-like sheath it was 0.96 $\mu cal/cm^2 \cdot sec$. Chadwick correctly sees the large amount of water in the sedimentary rock as the source. The general convergence of the conductive heat loss values for the shields is apparently related to the insignificance of the convective component.

TABLE 6. DISTRIBUTION OF THERMAL FLOW IN VARIOUS CONTINENTAL TECTONIC REGIONS
(By B. G. Polyak and Ya. B. Smirnov, 1968)

Tectonic Region	n	min	max	$\bar{q}$	$\sigma_{\bar{q}}$	L.C.	$\sigma_{L.C.}$	Distribution
Region of precambrian folding (non-segmented)........	128	0.53	1.33	0.93	± 0.02	0.17	± 0.01	Normal
Shields	75	0.61	1.32	0.90	± 0.02	0.15	± 0.01	"
Platforms	53	0.53	1.33	1.04	± 0.05	0.20	± 0.03	"
Regions of Caledonian folding .	24	0.68	1.71	1.11	± 0.07	0.28	± 0.05	"
Regions of Hercynian folding...	145	0.60	1.90	1.24	± 0.03	0.25	± 0.02	"
Regions of Mesozoic folding.... and activated in the Mesozoic..	26	1.00	2.12	1.42	± 0.06	0.31	± 0.04	"
Regions of Cenozoic folding.... and activated in the Cenozoic..								
Piedmont downwarps and intermontane depressions...	71	0.52	1.58	0.98	± 0.03	0.24	± 0.02	"
Folded mountain structures.. of myogeosynclinal zones...	32	1.20	2.20	1.75	± 0.06	0.25	± 0.04	"
Zones of Cenozoic vulcanism................	74	1.20	3.49	2.20	± 0.06	0.42	± 0.04	"
Continental rift zones								
N'yasa....................	20		1.00					Not established
Baykal....................	11	1.21	3.40	2.40	± 0.18	0.59	± 0.13	"

Note: n = number of thermal flow values; $\bar{q}$ = mean value; $\sigma_{\bar{q}}$ = standard mean error; L.C. = standard deviation; $\sigma_{L.C.}$ = error of standard deviation.

CHAPTER II /22

CHARACTERISTICS OF THE GEOLOGICAL STRUCTURE AND HYDROLOGICAL CONDITIONS IN THE AREA OF DAGESTAN UNDER STUDY

Geomorphology

The area under examination is administratively a part of the Dagestan ASSR and embraces a considerable portion of the eastern Ciscaucasia (eastern approach to the Caucasus) and the northern slope of the Caucasian Mountains. It is bordered on the northwest by the upper course of the Argun River, on the southwest by the water divide of the Main Caucasian Range, on the southeast by the Bazar-Dyuzi Massif and lower course of the Samur River, on the northeast by the shores of the Caspian Sea, and on the north by the lower reaches of the Kuma River.

A part of Dagestan corresponding geomorphologically to the priCaspian Lowlands is examined in this work. A southern region, or Dagestan Piedmont, and a northern, Plain of Dagestan, region are distinguished.

In the Dagestan Piedmont the Caspian Lowlands stretch in a narrow belt along the shores of the sea. Several marine terraces are noted here with elevations of 220-240, 135-140, 75-80, 50-55, and 15-20 meters. These terraces belong to the Neocaspian, Paleokhvalynsk, Neokhvalynsk, Paleo-khazarsk, and Bakinsk stages. In a number of cases the normal stratification of the deposits was disturbed by neotectonic movements, which is reflected in the hypsometry of the terraced benches.

North of Mt. Makhachkala the Caspian Lowlands become broader, occupying a considerable area of the Checheno-Ingushsk ASSR, the Stavropo Kray and the Oblast of Astrakhan. This part of it extending to the Sulak, Terek, and Kuma Rivers forms the Dagestan Plain. Within its borders two plains are morphologically distinguished; the Kuma and the Tersk-Sulak plains.

A large part of the Kuma Plain is occupied by sandstone massifs, the largest of which are the Kuma, Bazhigan, and the Terek. The locality has a slightly rolling contour with shallow oval or round depressions. The individual ridges of sand usually extend 5-10 km with widths of 1-3 km /24 and elevations of 15-30 m. In the central part of the territory, between the Kuma and Bazhigan areas, there are slightly undulating sandstone massifs and a slightly uplifted plain stretching from west to east; it is the natural water divide between the Kuma and the Sukhaya Kuma rivers. Characteristic of this part of the lowlands is the presence of short, dry beds of previously existing watercourses which extend in a latitudinal direction. The littoral of the Caspian Sea is a smooth plain with a large number of swampy areas overgrown with reeds. The absolute marks here are 20-28 m.

/23

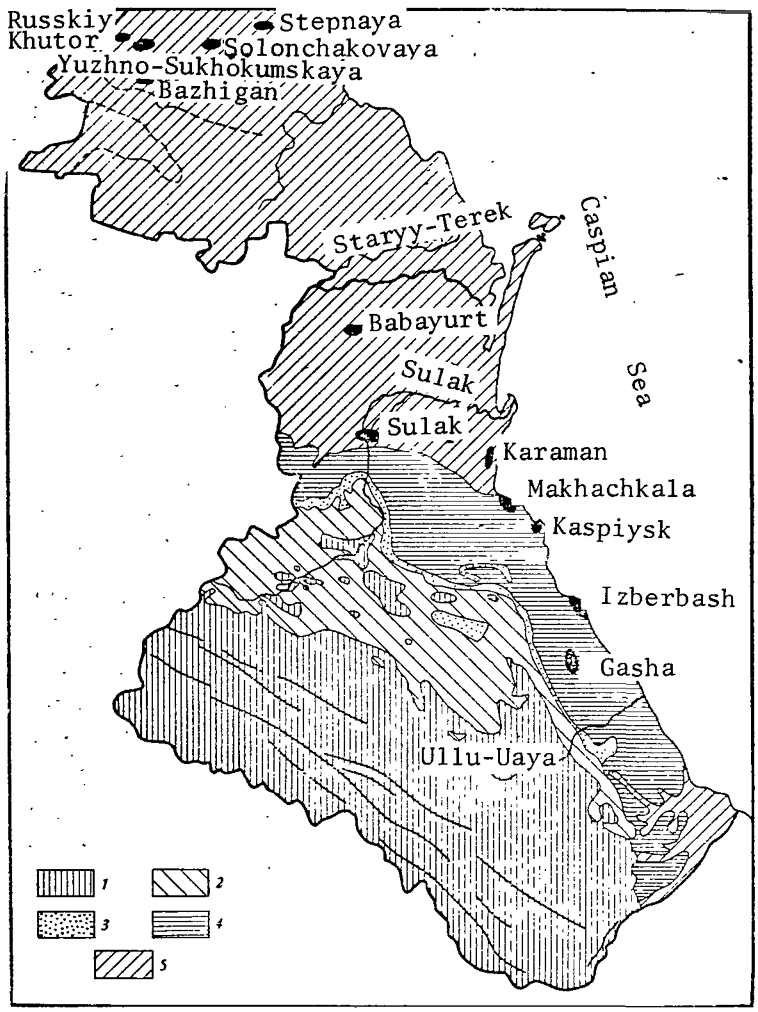

Figure 1. Distribution schematic of the investigated areas. 1, jurassic system deposits; 2, Cretaceous system deposits; 3, neogenic system deposits; 4, paleogenic system deposits; 5, quartenary deposits. Flooded investigated area.

The Tersk-Sulak Plain is bordered on the north and west by the Terek River, on the south by a belt of foothills, and on the east it is circumfluent by the Caspian Sea. Its surface is built up of alluvial deposits from the Terek, Sulak, Aktasha, and other rivers, while its coastal zone together with the adjacent islands and the Agrakhan Peninsula are built up of contemporary marine deposits. A slight inclination of the surface toward the east and northeast creates the impression of an ideal plain, which is disturbed only here and there by the presence of channel banks, low mounds, flat and enclosed depressions, and sandy mounds and ridges. Along the sea shore stretches a belt of sand dunes and ridges up to 10-15 m in height. Near the foothills the lowlands are intersected by dry washes and gulleys cut by the periodic run-off. In the central portion there are many shallow river valleys with smooth contours.

Tectonics

According to prevailing views (V. V. Belousov, I. O. Brod, M. S. Burshtar, P. A. Vardanyants, A. I. Letavin, M. F. Mirchink, M. V. Muratov, V. L. Rengarten, N. Yu. Uspenskaya, Yu. A. Sudarikov, and others), the territory which we examined is confined to two tectonic structures of different /25 ages: the Cenozoic Tersk-Caspian forward depression and the epihercynian Scythian platform.

In the southern part of the area studied, in the downwarp zone (sometimes called the Kulsar-Divichinsk Depression) two large anticline zones can be identified, the Eastern and Western, separated by a broad trough-shaped syncline. The "hinges" of both anticlines are formed by a series of brochyanticlinal uplifts. Both zones represent elements of the advance folding of the megaanticlinorium of the Greater Caucasus. The western anticline zone's surface is formed by rocks of Upper Cretaceous to the Pliocene, inclusive, with a predominant development of deposits of the Chokraksk and Karagansk horizons. One of the structures we examined, the Gashinsk brachy-anticlinal, is confined to this zone.

The eastern anticline zone is made up of Sarmatian stage rocks of the Konsksk, Karagansk, and Chokraksk horizons. In the anticline of the most uplifted areas (Berikey, Duzlak, Ogni) there are surface outcroppings of the Maykop formation clays. A thick cover of Paleocaspian formations overlies a large part of the area occupied by this structure and masks it. The area of Izberbash, which we studied, belongs to the Eastern anticline zone, while somewhat to the north are the areas of Kaspiysk and Makhachkala, which were also studied.

That part of the depression lying in the northwest is often called the Tersk-Sulaksk depression. This is a flatbottomed basin with sublatitudinal orientation which is filled with a thick layer of Cenozoic and Mesozoic deposits. In the opinion of many investigators (M. S. Burshtar, M. F. Mirchink, Ya. P. Malovitskiy, and ohters), a deep fracture with a latitudinal strike passes through the southern portion of this structure and is most clearly defined in the eastern part of the region.

Following the Maykop period, the Tersk-Sulaksk depression area underwent intense submergence. The removal of an enormous amount of terrigenous material from the elevated Caucasus completely compensated for the subsidence of this area and led to the accumulation of a layer of Middle Miscene-Quarternary sediments of a total thickness of 4-4.5 km. A Karaman well drilled to a depth of 4,437 m was still in the Karagan-Chokraksk deposits. The total thickness of the sediments which accumulated in the Tersk-Sulaksk depression during the Quarternary alone is more than 500 m, which indicates /26
the very intensive submergence of this area at the final stage of its development.

Several zones of uplift are encountered within the confines of the Tersk-Sulaksk depression (Western Aktash, Eastern Aktash, and Babayurt), and their geomorphological features give evidence of their neotectonic age.

The platform portion of Dagestan corresponds to the Kuma River zone of uplift of the Scythian platform, or the Kuma area arch. Its structure shows the effect of movements along the latitudinal tectonic lines (the Manych system of fractures and the proposed zone of the Kraynov stage), as well as that of transverse movements. The first led to formation of the arch and, according to the general opinion, were laid down at an earlier time, the second is reflected in its block structure.

Seismic exploration has established a large number of local uplifts in the sedimentary sheath of this area which are more clearly defined in the lower stratigraphic intervals and attenuate upward along the profile. These uplifts are platform-type brachyanticlines with amplitudes of 20-30 m and fold angles of dip up to 1.5°; their dimensions are 3-9 km along the long axis and 1.5-5 km on the short axis. They are all incorporated in three elongated arch-shaped groups with sublatitudinal strike: the Ozeksuatsk-Levokumsk, the Praskoveysk-Achikulasksk, and the Velichaevo-Maksimokumsk. The structures of Russkiy Khutor, Yuzhno-Sukokumskaya, Stepnaya, Solonchakovaya and Bazhigan, which we studied, are confined to the two latter groups.

Lithologic-Stratigraphic Description of the Profile

The region investigated is divided into two areas of different general geological development, which has left its imprint in the lithological-stratigraphical features of the rocks comprising the profile.

The oldest formations in Dagestan are deposits of the Paleozoic bedrock. They are greenish-gray siliceous and siliceous-micacesus slates and phyllites. Argillite, gray quartz-like hard sandstone, and, more rarely, dark gray and reddish limestone are encountered. In the Kuma River uplift region /27
(Bazhigan area) a 130-150 meter thick layer of light gray and greenish-gray marbelized dense limestone and recrystallized marl, arbitrarily related to the rocks of the folded base, was discovered at depths of 3,585 and 3,765 meters. These formations are dated as Middle-Upper Carboniferous (Bogdanovich, 1958; Tsaturov, 1957).

The factual data obtained in the course of geological investigations permit the hypothesis that as a result of tectonic movements in the pre-Jurassic period almost all of this territory was lifted above sea level and was dry land for some time. The result of this is that a considerable part of the Triassic and lower series of the Jurassic is absent from the profile.

The Jurassic system is represented by three series: upper, middle, and lower, of which the middle is the most completely represented.

Deposits of the Lower Jurassic are evident in the erosional basins of mountainous Dagestan and were uncovered in drill holes 2 and 3 in the Bazhigan area on the Dagestan Plain. The core material from hole 3 was tuffaceous sandstone and aleurolite, weakly cemented; in hole 2 it was psephitic, psammitic, and aleurolitic tuff, and quartzitic porphyrite. The thickness of the deposits is 150 m. The total porosity of the tuffaceous sandstone is 7-16%, the open porosity is 3-10%. No rocks of Lower Jurassic age were discovered by drilling on the Dagestan Piedmont.

Formations of the Middle Jurassic are represented by deposits of Aalen and Bayos-Batsk age. The Aalen deposits in the entire region studied are composed of argillites, aleurolites, and sandstones. In the Yuzhno-Sukhokumsk area between the Pre-Jurassic limestones and the Bayos sandstones there are argillite benches with aleurolite interlayers, 20 m thick. These deposits are arbitrarily dated as being of Toarcian-Aalen age.

The Bayos-Batsk deposits are aleurolitic-Argillaceous rocks. In the upper portion of the profile they are noticeably enriched by sandstones, sometimes quartzites with siliceous cement of the interstitial type. Within the borders of the Dagestan Plain (the areas of Yuzhno-Sukhokumskaya, Russkiy Khutor, Vostochno-Sukhokumskaya, Bazhigan, Solonchokovaya, and Stepnaya) the Bayo-Batsk deposits are represented by alternations of sandstone, aleurolite, /28
and black argillite, microbedded with pyrite inclusions. The total porosity of the sandstones does not exceed 8%, and the open porosity is less than 3%. Total thickness of the deposits varies from 550 to 800 m.

The Upper Jurassic strata are completely eroded away in the Piedmont area examined. In the Dagestan Plain the Upper Jurassic deposits are represented by a layer in which coarse strata of sandstone alternate thin strata of aleurolite, and above this dolomite and argillite strata alternate. Total porosity of the sandstones is 10-30%, the open porosity is 8-12%. Permeability varies from 43 to 430 millidarcy. Total porosity of the aleurolites is 8-10%, open porosity less than 3%.

Cretaceous deposits in the region studied are of two series (Lower and Upper Cretaceous) and have a total thickness of 500 m (Dagestan Piedmont) to 2,000 m (Dagestan Plain).

Lower Cretaceous deposits are sub-divided into two clearly defined lithologic-stratigraphic complexes: a lower, carbonaceous-terrigenous (Valanzhin and Goterivsk stages and Lower Barremsk sub-stage) and an upper, completely terrigenous (Upper Barrensk sub-stage, Aptsk and Al'bsk stages).

The entire lower carbonaceous-terrigenous complex is absent in the part of the Dagestan Piedmont which was studied. In the Dagestan Plain the Valanzhin-Goterivsk deposits are distinguished by variegated composition; primarily sandstones and limestones, to a lesser degree dolomites and argillites, aleurolites are encountered rarely. The accumulative properties of these rocks are not high; the total porosity of the sandstones is 18-12%, and in the limestones it is reduced to 6%. Maximum open porosity of the sandstones is 4-6%, and their filtration properties are poor.

The Barremsk deposits in the lower part are made up of sandstones and limestones, and higher in the profile appear layers of aleurolites and argillites.

The Aptsk deposits throughout the entire area are represented by sandstones, aleurolites, and argillites possessing good accumulative properties: total porosity of the sandstones varies from 4-20% and the open from 2-14%; for the aleurolites it is respectively 2-16% and 1.5-8%.

Lower Cretaceous deposits do not exceed 1,000 m in thickness. /29

Upper Cretaceous deposits, represented basically by pelitomorphic limestones, were found in the boreholes of the prospecting of the Dagestan Piedmont and Plain. They were not differentiated into individual stages in the Dagestan Plain; in the Piedmont they have been rather thoroughly studied.

Deposits of Senoman age are represented by a layer of marl-limestone. These rocks turn to Turonian arenaceous limestones which contain seams of marl. Deposits of Kon'yaksk age are similar in appearance to the underlying rocks. The Santonian stage is represented by light-gray, dense limestones, among which are found chalk-like limestones with horizons of stylolites. In the limestone bard of the Campanian stage, inclusions of silicon are often observed; the rocks are highly arenaceous. In the limestone layer of the Maastrikhtsk stage an increase is observed in the seams of marl and in the argillaceous constituents.

Total thickness of the Upper Cretaceous deposits is 200-260 m over the entire territory examined.

Paleogenic and Neogenic deposits, constituting a large part of the profile studied, play the most important role in the geologic structure of this region. The rocks of this age have a maximum thickness of 5,000-7,000 m.

Paleogenic deposits are subdivided into two lithologic-stratigraphic complexes: the Foraminiferous and Maykopian formations. The Foraminiferous series belongs to the Paleocene-Eocene formations, according to age, and constitutes a layer of marl-limestone. The Foraminiferous layers have an average thickness of 100-200 m in the piedmont and plain areas of Dagestan. The Maykopian series, corresponding to deposits of Oligocene and Lower Miscene age, is represented by a thick layer of brown and dark-gray clays containing seams of siderite, marl, aleurolites and sandstones.

In the territory under examination the Neogenic system is represented by both divisions, the Miocene and Pliocene.

The Miocene division includes the Tarkhansk, Chokraksk, Karagansk, and Konksk horizons (Middle Miocene), as well as the Samatian and Meotic stages (Upper Miocene).

In the Dagestan Piedmont the Chokraksk horizon is distinguished by non-uniform thickness and lithologic composition, which causes here a /30 segregation of three lithofacial regions. The northern region is characterized by arenaceous-argillaceous deposits, the central by aleurolitic-argillaceous, and the southern by argillaceous. In the Dagestan Plain the Chokrask horizon is expressed over a large part of the area by lithofacies of sandy appearance, which are divided here into a lower (Makhachkalin) and upper (Sernovodsk) series. In the Makhachkalin series the Upper Chokraksk horizon is represented by seams of clay and sandstone, distinguished by a high degree of sandiness and constant thickness (500-700 m).

In contrast to the Chokraksk deposits, the rocks of the Karagansk horizon are characterized by a high content of argillaceous and arenaceous strata. The thickness of these formations varies within narrow limits -- fromm 370 to 450 m.

Sarmatian deposits are widespread in the Sulak River area, in the environs of Makhachkala, and are traced in the form of mushrooms and ridges on the maritime plain of Southern Dagestan. Their total thickness reaches 800-1,900 m. The Sarmatian layer is composed of clays which become sandstones, to the south, with seams of calcareous aleurolites.

Meotic stage deposits are found only in the Sulak River region where they are represented by a 400-500 m thick layer of sandy clays and sandstones. Marls, clays, and sandstones predominate in the upper profile.

Pliocene rocks are limited to areas of large scale subsidence. In the areas of Northern Dagestan, Pliocene deposits are especially well developed on the southern slope of the piedmont depression. The Pliocene division has three subdivisions: a lower and middle corresponding to the continental layer of the Pontic stage, and an upper, including the Akchagil and Apsheron stages, which is composed of fresh-water continental rocks. The Akchagil strata are developed in the Sulak River region where they form a 300-350 meter thick arenaceous-argillaceous layer containing conglomerates and gravel in the upper part.

Quarternary rocks are most common on the maritime plain and in the ravines and river valleys in the fomr of marine and continental formations. The Pleistocene is represented by detrital limestones, conglomerates, sandstones, and clays. The first marine terrace is composed of loams, sandy /31 loams, snads, and sometimes weakly cemented craggy limestones of the Khvalynsk stage. The Holocene is represented by the Neocaspian stage, the deposits of which consist of sand, incoherent coquina, and aleurolite distributed in a narrow strip (1-2 km) along the littoral of the Caspian Sea. The Neocaspian deposits form ridges of maritime dunes over a considerable part of the littoral. All these terraces are composed of sand, conglomerate, and gravel. Deluvial deposits are usually loess-like loams. Early Quartenary rocks in Northern Dagestan vary in thickness from 400 to 520 m.

Hydrology

Corresponding to the geologic-structural features, two large hydrogeological regions can be distinguished in Dagestan:

1. The northern, including the Dagestan Plain and corresponding to the southeastern part of the Tersk-Kumsk artesian basin
2. The southern, including the Dagestan Piedmont, which belongs, basically, to the Greater Caucasus region, with the exception of the narrow strip of the Caspian Lowlands, and corresponding to the Dagestan artesian basin.

The Tersk-Kumsk artesian basin is considered a superimposed basin in relation to the larger Eastern Caucasian basin. Meso-Cenozoic deposits are involved in its structure. Water-permeable rocks of the Meso-Cenozoic sedimentary layer form several aquiferous complexes of regional extent.

Drill holes in the Bazhingan and Yuzhno-Sukhokumskaya areas revealed Middle Jurassic and Upper Jurassic-Lower Cretaceous aquiferous complexes. Lithologically they are represented by terrigenous deposits (sandstones and conglomerates). In the central part of the basin the waters in these complexes are characterized by considerable mineralization (50-150 g/l), and they can be classified as calcium chloride brines. For example, in drill holes in the Russkiy Khutor area mineralization of the waters in the Middle /32
Jurassic aquifers reaches 134 g/l, and that in the Lower Cretaceous aquifers is 126 g/l (Kissin, 1964).

The generally prevalent Upper Cretaceous aquiferous complex is confined to a layer of fractured limestones. It is characterized by a considerable abundance of water in the rock and a low mineralization (up to 36-60 g/l in the submerged portions) in comparison with the deeper-lying complexes. It is distinguished from them by an argillaceous layer of aptall [Note: Term undefined].

The aquiferous property of the Pliocene-Eocene rocks is not uniform. Water from this complex in the Bazhigan area was of the sodium sulfate type with 34 g/l mineralization. Highly mineralized waters were also discovered in the other areas.

The Maykopian aquifierous complex is particularly well developed in the territory studied but its hydrogeological significance is not great. It includes several water-bearing horizons confined to layers of sandstone. The number and capacity of these horizons increases northward from the piedmont plain where the Maykopian deposits (primarily argillaceous rocks in this area) crop out on the surface. The mineralization of the waters from the Maykopian deposits varies within considerable limits, depending on the depth of the strata and the degree of permeability of the water-bearing rock. The highest mineralization was found in the holes of the Sukhokumskaya area (28 g/l); it diminished toward the northeast to 8-18 g/l (Bazhigan).

Lying higher along the profile, the Middle Miocene (Chokraksk and Karazansk), Upper Sarmation, Pliocene, as well as the Akchagyl'sk, Apsheronsk, Bakinsk, and Kharzarsk aquiferous complexes are characterized by low capacities, shallow depths, and good filtration properties. The waters of these complexes are weakly mineralized and characterized by different chemical compositions, but sodium hydrocarbonate waters predominate.

Within the borders of the Dagestan artesian basin are several basins of secondary rank, confined to the Karamayaul trough, the Buynak syncline, the Sanursk depression, and others. The same water-bearing complexes are involved in its structure that are found in the Tersk-Kumsk basin. The super-Maykopian aquiferous complexes are the most studied of these since the older deposits were revealed only on portions of the anticlines, and in /33 the central parts of the basin they are deeply buried. For example, in Karaman (the axial portion of the basin), a hole 4,437 m deep was still in the Chokraksk deposits. The thickest of the super-Maykopian complexes (the Chokraksk and Karagansk) are represented lithographically by aleurolites, sandstones, and sands with interstratifications of agrillaceous-carbonaceous rocks. Their thickness decreases in the northerly direction toward the Dagestan Plain, reaching a maximum in the piedmont belt (in the area of

Makhachkala and Karaman). The high permeability of the arenaceous rocks in these horizons results in a high rate of discharge from the wells and a relatively low mineralization of the water. For example, in Makhachkala at the depth of the Chokraksk horizon around 1,600 m the water mineralization is 3.3 g/l; in the Karazansk horizon at 1,490 m it is 3.5 g/l.

The higher lying aquiferous complexes of the Pliocene deposits contain water with low mineralization and serve as the water supply.

A study of the recharge, flow and discharge, the results of which are correlated in the works of S. A. Shagoyants, I. G. Kisin, and other authors, shows that the recharge of the water-bearing complexes of the above two artesian basins takes place in the piedmont of the Caucasian Range and the discharge--in the sunken areas of the Caspian Lowlands. Many investigators suggest that a vertical filtration of the water occurs in the plains section of Dagestan from the lower lying aquifers through the relatively impermeable rocks into the upper aquifers. In connection with this it is possible that an exchange of water is activated in the deep water-bearing horizons also, in the Chokraksk and Karazan horizons for example.

Waters of the sub-Maykopian aquiferous complexes in the submerged areas of the Tersk-Kumsk and Dagestan basins are characterized by a high degree of mineralization, from 136 to 34 g/l, and sodium chloride composition, and form a zone of very slow water exchange. The aquifers of the Maykopian layer in the axial portion of the basin (Karaman) also belong to this very slow exchange zone. The aquifers of the higher lying Chokraksk-Karagansk and Samartian deposits are characterized by a lower mineralization (up to 20 g/l) and belong to the zone of slow water exchange. The aquiferous complexes of the Pliocene deposits have the lowest mineralization and belong to the zone of active water exchange.

CHAPTER III /34

GEOTHERMAL GRADIENT

In the study of the geothermal conditions in the Eastern Caucasus the investigations of F. A. Makarenko, D. I. D'yakonov, A. Ya. Dubinskiy, G. M. Sukharev, A. S. Dzhamalova, V. M. Nikolayeva, V. A. Pokrovskiy, B. G. Polyak, V. N. Kortsenshtein, I. G. Kissin, and others have played an important role. The spatial principles of the geothermal field within the territory being studied were quite thoroughly and objectively illuminated in their works, which freed us from the necessity of regional geothermal analysis. But in the exact calculations of the thermal flow it was not always possible to make use of previously established values for the geothermal gradients since insufficient attention was given in the previous works to evaluation of the equiponderance of these values. Often they were derived from extrapolated temperatures or determined according to thermal logging material without any evaluation of their quality. Therefore we devoted primary attention to clarification of the magnitudes of the vertical temperature gradients corresponding to the natural thermal field in the portions of the profile studied in 12 areas: Gasha, Izberbash, Kaspiysk, Makhachkala, Sulak, Babayurt, Karaman, Yuzhno-Sukhokumskaya, Russkiy Khutor, Solonchakovaya, Stepnaya, and Bazhigan.

Evaluation of the Quality of the Factual Material

Evaluation of the geothermal conditions of the region, exposure of the principles of temperature changes with depth within the range measured, the possibility of temperature extrapolation within its limits, and other geothermal structures must be based, above all, on quality thermometric material. From this point of view, an analysis of the conditions under which the /35 measurements are made is very important. The drilling of wells disturbs the natural conditions of heat transfer, which distorts the picture of the temperature distribution according to depth.

In evaluating the temperature gradients we proceeded according to the quality of the different materials: thermal logging diagrams, results of spot measurements by maximum thermometer in wells with a steady thermal regimen, and data on temperature measurements with a maximum thermometer in hydrogeological and prospecting testing of wells.

Thermal logging data are not completely reliable because of insufficient stabilization of the wells, and we employed it only in the event it was possible to calculate the equal importance of the geothermal gradients by comparing the results of several observations.

Numerous thermometric data were obtained in hydrogeological and industrial investigations. Temperature measurements of the water entering the wells, made at depths no more than 50-70 m above the filter, are sufficiently exact to reflect the natural temperature in the stratum being tested.

Before drilling, there exists in each elementary layer a vertical thermal flow which corresponds to the arrival of heat from the layer below and its generation (accumulation) in the given layer. These thermal conditions cannot be maintained in the shaft of a well, basically because of changes in the thermal conductivity of the medium.

In all cases, if the well is only lined with drilling mud or cased, the conditions of heat exchange are altered not only in the well itself but also in the part adjacent to the shaft. The thermal conductivity of the drive pipe metal or the cement casing is considerably higher than that of the rocks, while the heat exchange conditions are better in the drilling mud than in the surrounding layer of rock. All this corresponds to an intensified outflow of heat from the bottom hole to the surface and results in a reduction of the temperature in the area of the bottom hole in comparison to the surrounding rocks.

The degree to which the temperature is disturbed depends on the toughness of the rock in which the well is being drilled, the duration of the drilling, temperature of the drilling mud, and the depth and diameter of the hole. The time necessary to reestablish equilibrium, called the well stabilization time, /36
depends on these factors.

The circulation of a flushing fluid in the well produces a fundamental disturbance of the natural temperature regimen (E. Bullard, Dzh. Eger,

E. A. Lyubimova, and others). The geothermal gradient along the shaft is equalized; an increase in the temperature in comparison with the normal is observed in its upper portion, and a decrease, on the other hand, in the lower part.

Calculations show that in precise geothermal measurements the time which the well must stand to achieve thermal equilibrium is considerably greater than the time required for circulation of the drilling mud to a given depth. For the measurement of rock temperatures with relative accuracy, to 0.01 for example, the necessary standing time must exceed the circulation time of the flushing fluid 10-20 times. The results of full scale observations confirm that the standing time varies within broad limits, from several weeks up to 2-3 years.

The period of time for which a well must stand, following drilling, until the natural thermal field is reestablished, has been estimated theoretically by a number of investigators (E. Bullard, Dzh. Eger, A. Lachenbruch, M. Brewer, V. N. Dakhnov, D. I. D'yakonov, I. M. Kutasov). Several schemes were examined simplifying presentations of the disturbance processes produced by drilling and by the circulation of drilling mud.

Drilling conditions vary for different countries and areas. In diamond drilling the shafts are primarily of small diameter, which considerably reduces the consumption of drilling mud. This results in a reduction of the rock temperature difference as well as that of the mud, i.e., a reduction of the disturbance. In addition, the rate of penetration is increased and the stabilization period shortened. Dzh. Eger presented some interesting data in 1961 on the reestablishment of the temperature regimen in such wells. It was shown that the geothermal gradient was measured with an accuracy of up to 5% of its true value in shafts of 1.9 cm radius and at a depth of 530 m after 18 hrs of standing; at that time the absolute temperatures along the shaft of the well still differed noticeably from the natural temperatures of the rock mass. In precise geothermal investigations in which changes in the thermal flow are manifested, it is necessary to /37
consider the actual drilling conditions which characterize the given region.

The geothermal gradient is a differential quantity, therefore reestablishment of its true value differs from the process of the reestablishment of temperatures along the well shaft. Evaluation of the equivalent temperature gradients was made by the "dual thermogram" method developed by I. M. Kutasov (Kutasov, Lyubimova, Firsov, 1966) for predicting natural rock temperatures. This method is based on utilizing data concerning two temperature distributions, each of which is recorded under the condition of insufficient stabilization of the well. With two thermograms (T_1, T_2), taken at different periods of stabilization ($t_2' = t_{2,1}$; $t_2'' = t_{2,2}$), the method permits prediction of the constant natural temperatures. It was derived, that

$$T_n = T_2 + \gamma(T_1 - T_2),$$

the coefficient of correlation is found from the equation

$$\gamma(t_2, t_1) = \frac{E_i\left(-\frac{D_1}{n_2}\right) + \ln n_2 - D_2}{E_i\left(-\frac{D_1}{n_2}\right) - E_i\left(-\frac{D_1}{n_1}\right) + \ln\frac{n_2}{n_1}},$$

where: $n_1 = t_{2,1} : t_1$; $n_2 = t_{2,2} : t_1$; $D_1 = 1.1925$; $D_2 = 0.7532$; t_1 is the circulation time of the drilling mud to a given depth; $E_i(-x)$ is the integral exponential.

In those cases where we did not have reliable data in the form of spot temperature measurements in long-standing wells, we employed existing thermal logging material for computation of the equivalent gradients by the "dual thermogram" method, which is sufficiently simple and effective in our opinion.

Special Features of the Geotemperature Regimen in the Dagestan Regions Studied

We shall determine briefly the geotemperature regimen of the areas studied.

Karaman. Several thermograms were taken in the Karaman-I well in this area. The interval of 2,800-4,000 m was determined by a threefold thermal measurement: 16 December, 1965; 28 February, 1966; and 16 March, 1966. The equivalent gradient was determined by the "dual thermogram" method (Figure 2). /38

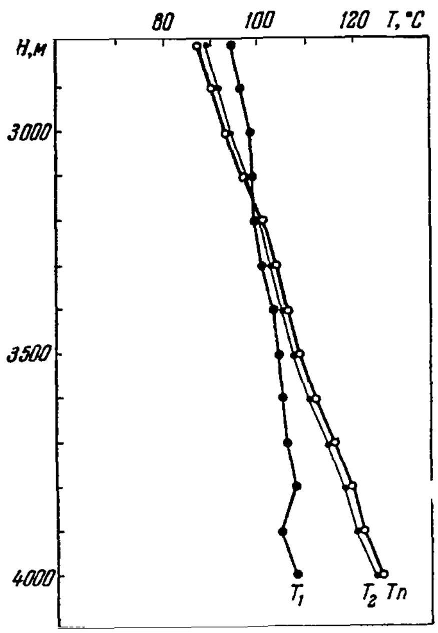

Figure 2. Results of computation of the natural temperatures of the rock along the Karaman-I well shaft at 2,800-4,000 m depths by the "Dual Thermogram" method.

T_1, observations of 16 December, 1965;

T_2, observations of 16 March, 1966;

T_n, computed temperature.

The first measurements were made 0.25 days after the completion of the drilling process and the third set of measurements was made 90 days after completion. Later, following a prolonged interruption, drilling was resumed but in view of the fact that there was no information concerning the reestablishment of the temperature field in the well at depths greater than 4,000 m (one thermolog was made of the interval 4,000-4,437 m before the well was sufficiently stabilized), reestablishment of the temperature field was examined only /39 for the 2,800-4,000-m interval. The formulas employed are given above. In this case $t_{2,1}$ = 0.25 days, and $t_{2,2}$ = 90 days. The value t_1 was calculated for a uniform rate of drilling within the interval of 2,800-4,000 m. It is known that drilling of this interval took a period of 250 days.

The dependence of the value t_1 on the running depth of the hole H may be expressed by the following equation:

$$t_1 = 250\left(1 - \frac{H - 2800}{1207}\right).$$

The results of the calculation of the values γ_t and T_n according to the given formulas are presented in Table 7 and reflected in Figure 2.

As was to be expected, in the near vicinity of the bottom hole the coefficient of correlation γ rapidly approaches 0. As a result of this, T_2 tends toward T_n as it approaches the bottom hole.

The average temperature gradient across the whole profile under study varies from 0.023 to 0.04 °C/min.

TABLE 7. RESULTS OF THE ANALYSIS OF TEMPERATURE DATA ON THE KARAMAN WELL BY THE "DUAL THERMOGRAM" METHOD

H	T_1, °C ($t_{1,1}$ = 0,25 days)	T_2, °C ($t_{2,2}$ = 90 days)	(T_1-T_2), °C	γ	$\gamma(T_1-T_2)$	T_n
2800	94,6	89,1	+ 5,5	0,304	−1,57	87,5
2900	93,4	91,6	+ 4,8	0,289	−1,38	90,2
3000	96,8	94,1	+ 2,7	0,275	−0,73	93,4
3100	98,7	97,7	+ 1,0	0,258	−0,26	97,4
3200	99,7	100,7	− 1,0	0,241	+0,24	100,9
3300	101,2	103,5	− 2,3	0,221	+0,51	104,0
3400	103,5	105,8	− 2,3	0,201	+0,46	106,3
3500	104,8	108,4	− 3,6	0,178	+0,64	109,0
3600	105,6	111,6	− 6,0	0,152	+0,91	112,5
3700	106,3	115,3	− 9,0	0,124	1,12	116,4
3800	108,5	119,2	−10,7	0,092	0,99	120,2
3900	105,3	121,3	−16,0	0,063	1,00	122,3
4000	108,7	126,0	−17,3	0,0085	0,15	126,2

Note: Commas indicate decimal points.

Makhachkala. Two thermograms were taken, on 27 February 1966 and 12 March 1966, in well 215 of this area at 100-1,750 m depths (Figure 3). /42
The equivalent gradients of temperature were calculated on the basis of these data. The well was investigated a third time at the 1,400-1,700 m interval after a two month stabilization period. The derived values of the gradient agree with the equivalent values calculated from the foregoing data by the "dual thermogram" method. Here they vary from 0.022 to 0.031 °C/m.

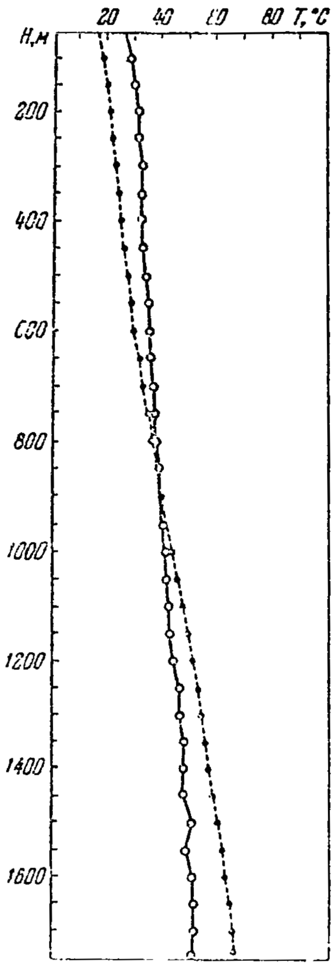

Figure 3. Temperature changes with depth in the Makhachkala-215 well.

Solid line, stabilization time of the well before measurement = 10 hrs; dotted line, stabilization time = 13 days.

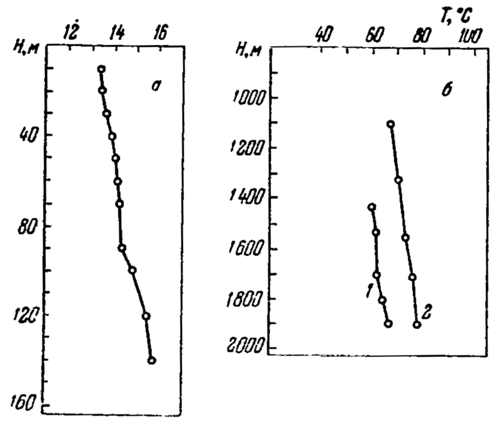

Figure 4. Temperature changes with depth in the Izberbash area.

a, Well 2-R; b, Well 235(1), well 237 (2).

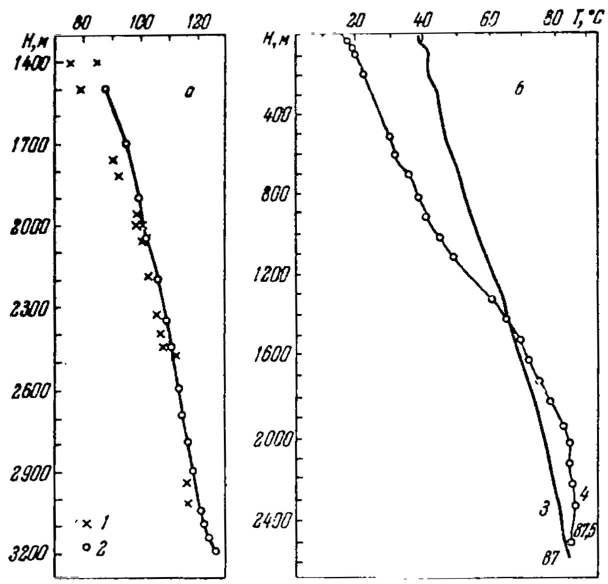

Figure 5. Temperature changes with depth in the Gasha area. a: 1, spot measurements of temperature in hydrogeological investigations; 2, thermolog results from well 29; b: 3, the same for well 2, stabilization time = 10 hrs; 4, the same, stabilization time = 10 days.

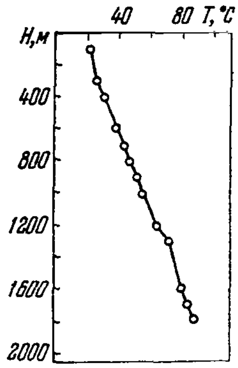

Figure 6. Changes of Temperature in Relation to Depth in the Kaspiysk Field (Well No. 3-T).

Izberbash. A large number of results of spot measurements and thermograms exist for this area, which were taken in various wells (Figure 4). The natural temperatures of the rock were calculated from the data of observations over many years in the operating well 2-P (Figure 4, a). The average equivalent gradient was calculated for the 10-140 m interval (it is 0.034 °C/m). Thermograms were taken in adjacent wells 237 and 235 with a one-month stabilization (Figure 4, b). The temperature gradients evaluated according to it in the 1,216-1,962 m interval vary from 0.013 to 0.018 °C/m.

Gasha. A large number of thermometric measurements were made in this area (Figure 5). In the 2,130-3,140 m interval, where the thermal flow was studied, the gradient values determined by the thermogram of well 29 and those by the spot measurements in the adjacent wells, made during the testing of the strata, are close, which confirms the correspondence of the temperature distribution recorded in well 29 with the stationary thermal field. The gradient values according to the thermogram vary from 0.018 to 0.019 °C/m.

Kaspiysk. In this area spot measurements were made with a maximum thermometer following a one-month stabilization in well 3-T at depths of 100-1,800 m (Figure 6). The exposure time for each reading was 30 min. In the 1,420-1,864 m interval, where the thermal conductivity of the rock was studied, the temperature gradient values varied from 0.023 to 0.05 °C/m.

Babayurt. Spot measurements were not made in this area and the gradient values were evaluated by the results of the thermolog of well No. 1, made after one month of stabilization (Figure 7). The temperature gradient in the 500-600 m interval was 0.019 °C/m. /43

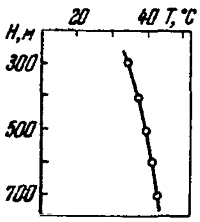

Figure 7. Temperature Changes in Relation to Depth in the Babayurt Field (Well No. 1).

Sulak. In this area, where there was good opportunity to study the thermal conductivity of the rock, no thermometric observations were made. For calculation of the thermal flow here gradient values were employed which had been established for the adjacent Karamansk area, the geologic-hydrological conditions of which are nearly the same. In the interval studied their values varied from 0.024 to 0.025 °C/m.

For all the investigated areas considered below, there existed thermograms which were taken with no less than one month's stabilization, as well as spot measurements of the temperatures. But in all cases the equivalency of the gradients was evaluated additionally by the "dual thermogram" method.

Yuzhno-Sukhokumskaya. In this area thermal logs were made of several wells which had been inoperative for periods of from several days up to 11 months, and spot measurements were made with a mercury thermometer with one month stabilization and during the process of testing the strata. Thermometric observations were made at depths of 500-3,700 m (Table 8 and Figure 8).

The equivalent average geothermal gradient, determined after prolonged stabilization of the wells and evaluated by checking with the "dual thermogram" method, was 0.04 °C/m for the 500-2,500 m interval and 0.024 for the 2,560-3,410 m interval. For the 2,500-3,700 m interval which was studied thermophysically the equivalent temperature gradient was 0.023 °C/m.

Russkiy Khutor. The rock temperatures here are close to those in the Yuzhno-Sukhokumskaya area. For example, in well No. 13, located in the dome of the structure, a temperature of 124 °C was recorded at 3,080 m, and 134 °C at 3,380 m. In well No. 16, located on the northern edge, the temperatures, measured with a maximum thermometer during testing of the Lower Cretaceous /44
oil-bearing strata, were 113.5 °C at 2,700 m and 126°C at 3,200 m. The average geothermal gradient, computed according to the equivalent distribution

of temperatures using all existing data (Figure 9), was 0.026 °C/m in the portion of the profile studied in the Russkiy Khutor area.

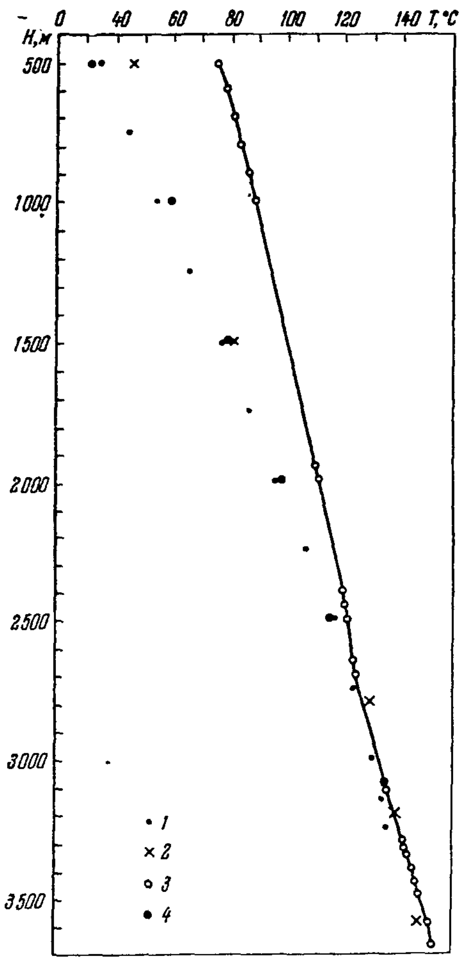

Figure 8. Temperature changes with depth in the Yuzhno-Sukhokumaskaya area.
1, Results of measurements with a mercury thermometer in well No. 4 after 1 month of stabilization (V.N. Kortsenshteyn); 2, data obtained from wells No. 14 and No. 16 during testing of the strata; 3, results of thermolog of well No. 2 in production tests; 4, the same, after 11 months stabilization.

Solonchakovaya. Spot measure- /45
ments of the strata temperatures were made with a maximum thermometer in wells No. 2, 3, and 5 of this area. The 2,650-3,700 m interval /46
was determined. Maximum temperature (at the bottom of the interval) was 145°. The geothermal gradient in the portion of the profile studied varied from 0.025 to 0.017 °C/m.

Bazhigan. The temperature distribution was studied in wells No. 2 and 4 of this area at depths from 3,600 to 4,000 m (Figure 10). The geothermal gradient here varied from 0.044 to 0.036 °C/m.

Stepnaya. Distribution of the equivalent values of the rock temperatures in this field are shown in Figure 11.

Analysis of the existing factual data by the "dual thermogram" method made it possible to determine the equivalent values of the geothermal gradient at different intervals of the profile for the /47
fields under study. As a result, the following temperature gradient values (in °C/m) were established for the terrigenous-carbonaceous

rocks of Mesozoic age in the different fields (deg/m): Gasha (2,130-3,146 m), 0.18-0.19; Russkiy Khutor (2,335-3,395 m), 0.023-0.033; Yuzhno-Sukhokumskaya (2,500-3,730 m), 0.23; Stepnaya (2,500-2,950 m), 0.025; Solonchakovaya (2,900-3,552 m), 0.017-0.025.

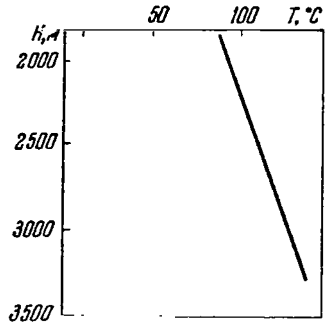

Figure 9. Equivalent distribution of temperatures with depth in the Russkiy Khutor field.

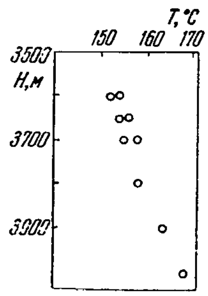

Figure 10. Temperature changes with depth in the Bazhigan field.

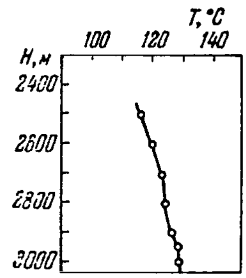

Figure 11. Temperature changes with depth in the Stepnaya field.

In the argillaceous rocks of the foraminiferous horizon and the Maykopian formation in the Yuzhno-Sukhokumskaya field the equivalent gradient was 0.035 °C/m in the 1,900-2,300 m interval.

In the sandstones and arenaceous clays of Karagan-Chokraksk age, the temperature gradients (in °C/m) in the different fields are distributed in the following manner: Izberbash (576-1,900 m), 0.016-0.18; Kaspiysk (1,420-1,864 m), 0.023-0.05; Makhachkala (1,400-1,700 m), 0.022-0.031; Karaman (3,736-4,437 m), 0.039.

In the clays of Apsheronsk age the values of the temperature gradients for the Babayurt, Sulak, and Karaman fields, respectively, were 0.019 (500-600 m), 0.024 (300-500 m), and 0.024 (469-1,051 m).

Gradients of 0.36 and 0.042 °C/m were obtained for the marbelized limestones of the folded bedrock in the Bazhigan field.

As is evident from the data presented, a tendency of the temperature gradient to increase in value within one and the same lithological-stratigraphic complex in a south to north direction can be traced in the gradient distribution over the territory studied. This may be related, more than to anything else, to the effect of the hydrogeological factor (the southern part of the territory studied is the recharge region, and the northern part is the region of subterranean drainage).

TABLE 8. RESULTS OF TEMPERATURE MEASUREMENTS IN WELLS IN THE YUZHNO-SUKHOKUMSKAYA EXPLORATION AREA (ACCORDING TO DATA BY A. I. KAMYSHNIKOVA, 1963)

No. of well	Date of reading	Period of stabilization	Depth, in meters											
			500	1,000	1,500	2,000	2,100	2,400	2,500	2,700	3,000	3,100	3,200	3,350
2	July, 1960	11 mos.	31	58	77	95	--	--	111	--	--	130	--	--
3	"	7 mos.	--	--	77	94	--	--	--	--	--	129	--	--
4	"	24 hrs.	--	--	--	94	--	--	111	--	--	123	128	--
5	"	8 mos.	34	53	78	94	--	--	112	--	123	127	--	--
6	Jan., 1961	No data	--	--	74	--	95	105	--	116	126	--	--	--
7	"	4 mos.	--	--	--	--	--	--	--	--	--	--	--	134
9	June, 1961	No data	--	--	--	--	--	--	--	--	--	--	130	134

CHAPTER IV /48

THERMOPHYSICAL PROPERTIES OF ROCK

Thermophysical Properties of Rocks and Methods of Studying Them (General Information)

For correct interpretation of geothermal data and the solution of a series of problems associated with the utilization of subterranean heat it is necessary to know the thermal constants of rock. The generalized tabular data presented in the literature cannot be used in precise calculations for the purpose of clarifying the distribution of thermal flow according to depth in actual profiles. For this the individual values must be determined for the thermal conductivity of the rock in thermometrically investigated depth intervals.

The thermal conductivity of non-metallic substances is determined by oscillation of their crystal lattice. The characteristic of rock is contained in the fact that it is a polycrystalline compound consisting of several components. Neither the theory of solid bodies nor the relationships for dispersed fluids is always applicable for describing their properties.

Geophysical data concerning the electro-conductivity of the Earth's upper layers confirm that the change in the resistance of rock which occurs with a change in temperature is similar to that of dielectrics, insulators, and semiconductors. Curves of the relationship of thermal conductivity of rock to temperature are presented in Figure 12. Obviously, the thermal conductivity of rock is reduced with the temperature. It is known that the thermal conductivity of semiconductors also falls with the temperature at first (Kingery, 1954; Devyatkova, 1957; Kittel', 1958; Ioffe, 1960, Figure 13). This analogy makes possible the applications of the results of the physics of /49 semiconductors and non-metallic compounds to the description of the thermal properties of rock.

The thermal conductivity λ of non-metals is described in the theory of solids by the equation $\lambda = \lambda_0 \Theta/T$, where T is the current temperature;

Θ is the characteristic Debye temperature, depending on the oscillation spectrum of the substance; λ_o is a constant depending on the crystal lattice structure (Leybfrid, 1963). Determining λ_o empirically it is possible to use the formula for describing the properties of rock with an increase in temperature and pressure.

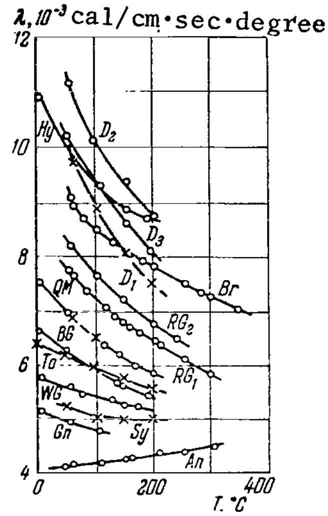

Figure 12. Curves of the relationship of thermal conductivity to temperature (Birch, Clark, 1940).

D_1, D_2, D_3, dunites; Hy, hyperstennites; Br, bronzite; RG_1, RG_2, Rockport granites; BG, Barr granite; QM, quartzitic monzonite; Gn, gneiss; WG, Westerly granite; Sy, syenite; An, anorthosite; To, tonalite.

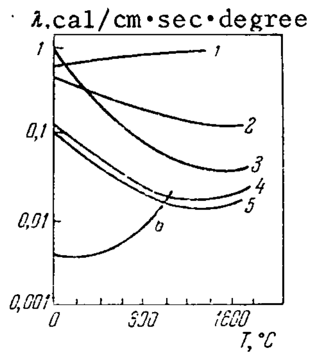

Figure 13. Relationship of thermal conductivity to temperature (Ye. A. Lyubimova et al., 1946b).

1, platinum; 2, graphite; 3, BeO; 4, MgO; 5, Al_2O_3; 6, quartz.

Investigations conducted by different authors have shown that the composition and structure of rocks, as **well** as the thermodynamic conditions in which they are found, affect their thermal conductivity. /50 It has been established, that the thermal conductivity of sedimentary rocks of uniform composition depends very strongly on moisture and porosity.

In absolutely dry, porous material, heat transfer may proceed through the hard skeleton and through the air in the rocks. There may also occur an internal exchange of heat between the walls of the pores in the form of radiation from the walls and convection of the air in the pores.

In the heating and cooling of moist materials, processes of heat and mass exchange take place (Lykov, 1956a) during which the kinetics of the heat and mass transfer are determined by the difference of transfer potentials. The thermal conductivity coefficient of the material increases in proportion to the increase of moisture content (Bab'yev, 1954). Analyzing this relationship V. D. Shevel'kov (1958) came to the conclusion that the abrupt initial increase in the coefficient of thermal conductivity and thermal diffusivity with a rise in the moisture content of the material occurs because the replacement of air by water improves the thermal contact between the particles. This question was investigated repeatedly in theory, but no satisfactory correspondence with experimental results could be achieved. Examining heat transfer in an idealized structure, A. F. Chudnovskiy (1954) set up the general approximation formula

$$\lambda = \lambda_0 \left(\frac{d\lambda}{dW_0}\right) W_0,$$

where λ is the coefficient of thermal conductivity for a moisture-containing material; λ_0 is the coefficient of thermal conductivity for the same material in the dry state; W_0 is the volume of moisture in %; and $d\lambda/dW_0$ is the increment in the volume of moisture by 1% (specifically defined for each material experimentally). In the initial stage of moistening the thermal conductivity may be considered as a linear function of moisture $\lambda = f(W)$, but with a 50% increase and higher in porosity the theory indicates a deviation from a straight linear dependency.

Some polyempirical schemes and mathematical models still exist. For example, Horai and Uyeda (1960) make use of Bullard's formula /51

$$\lambda = K_w \frac{3 - 2v\left(1 - \frac{K_w}{K_s}\right)}{\frac{3K_w}{K_s} + v\left(1 - \frac{K_w}{K_s}\right)},$$

where K_W is the thermal conductivity of water; K_S is the thermal conductivity of solid particles; v is the moisture content by weight (W_{weight}):

$$v = \frac{W_{moisture}}{[W_{weight} + (1 - W_{weight}) \rho_W/\rho_S]},$$

where ρ_W is the density of water, ρ_S is the density of solid particles. B. I. Kaufman (1955) proposes the formula

$$\lambda_w = \lambda\left(1 + \frac{wf(w)}{100}\right),$$

where f(W) is the increment (in %) of the coefficient of thermal conductivity of the dry material for each percent of volumetric moisture of the material. For inorganic materials of mixed composition $f(W) = 1.15 - 6.05\,\gamma + 14.3$, where γ is the volumetric weight. The value of Kaufman's work lies in the fact that he establishes the values f(W) for the individual classes of thermal conductors, which permits the effect of the structural differences of actual materials on the thermal conductivity to be taken into account.

In Figures 14-16 are shown experimental curves of the dependency of thermal conductivity on porosity and moisture in natural mediums. The different nature of the curves for fine and coarse grained materials, and for porous and crushed substances, is explained by the specific distribution of water and air in the mineral mass in each case.

We also carried out special experiments to clarify the dependence of thermal conductivity on the moisture content of rocks. The dry specimens of clay, sandstone, argillite, and aleurolite have the lowest thermal conductivity, as would be expected. This is related to the low thermal conductivity and thermal capacitance of the air in the interstices. Replacement of the air by water substantially increases the thermal conductivity. Our experiments indicate that the thermal conductivity of rock with natural moisture content exceeds that of the dry rock by up to 15%, and sometimes even up to 30% (in water-bearing sandstone). /52

Decrease in the thermal conductivity of rock with an increase in temperature amounts to 0.1-0.3% for 1°C for various lithographic types, according to measurements by different authors (Birch, Clark, Greutzburg, Roy).

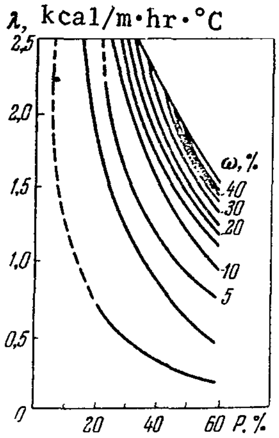

Figure 14. Dependence of thermal conductivity on porosity when moisture content is constant (Ye. A. Lyubimova et al., 1964b).

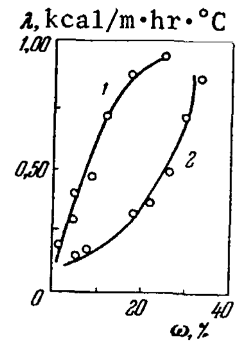

Figure 15. Dependence of thermal conductivity on moisture content for coarse-grained (1) and fine-grained (2) materials (Ye. A. Lyubimova et al., 1964b)

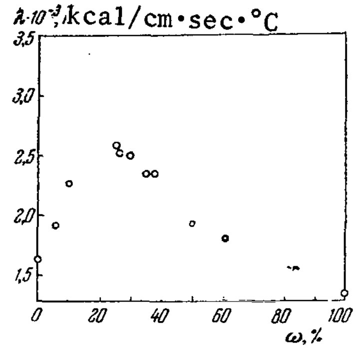

Figure 16. Dependence of thermal conductivity on moisture content for crushed materials (Horai, Uyeda, 1960).

Methods for measuring the coefficient of thermal conductivity of rocks in the laboratory have been described in many works (Lykov, 1952, 1956a; Lyubimova et al., 1964b; Shevel'kov, 1958; Kondrat'yev, 1954; Birch, Clark, 1940; A. Beck, J. Beck, 1958). They are all based on the solution of the thermal conductivity equation

$$\lambda\left(\frac{d^2T}{dx^2}+\frac{d^2T}{dy^2}+\frac{d^2T}{dz^2}\right)=\rho\cdot c\frac{dT}{d\tau}$$

and are divided into two basic groups: a) methods of steady thermal flow and /53
b) methods of variable thermal flow. The latter are sometimes subdivided (Shevel'kov, 1958) into methods of regular thermal regimen, quasi-steady thermal regimen, and methods based on determination of the parameters of a variable thermal field in the first stage of its development.

Primarily it is the steady state methods which have been developed for determining the coefficient of thermal conductivity. In the 1880's modifications of them had been worked out which permitted determination of the coefficient of thermal conductivity of different porous materials with an accuracy sufficient for that time.

Methods of Steady Thermal Flow

The methods for determining the coefficient of thermal conductivity of materials in a steady state are based on the equation $Q = \Phi\lambda\Delta T$, where Φ is the form-factor characterizing the geometric form and dimensions of the specimen; Q is the thermal flow; T is the temperature drop in the test specimen; and λ is the thermal conductivity.

In investigations by the method of steady thermal flow a thermal flow of constant intensity is passed through a specimen of a given geometric form.

The most common methods for a flat, spherical, or cylindrical stratum are based on solution of the thermal conductivity equation when $dT/d\tau = 0$. The formula for calculating a flat layer is:

$$\lambda = \frac{Qx}{S(T_1 - T_2)},$$

for a cylindrical it is:

$$\lambda = \frac{Q \ln \frac{r_1}{r_2}}{2\pi x(T_1 - T_2)},$$

and for a spherical it is:

$$\lambda = \frac{\left(Q \frac{1}{r'} - \frac{1}{r''}\right)}{2\pi(T_1 - T_2)},$$

where Q is the amount of heat flowing from one isothermic surface to the other; x is the thickness of the stratum; S is the area of the plate; r_1, r_2 are the upper and lower radii of a cylindrical stratum; and T_1 and T_2 are the temperatures of two isothermic surfaces. /54

Many experimental devices have been designed in conformity with these mathematical models. Their capacity to measure the magnitude of thermal flow is different for the different variants. Most often it is computed by recording the force of the energy being consumed. There are instruments which compute the thermal flow by determining the change in heat content of a substance located in thermal contact with the test specimen, or by employing thermometers (Fokin, 1949). For the elimination of thermal leaks, which are difficult to take into account, instruments are equipped with various protective devices. These are proposed as various means of calculating the magnitudes of heat leaks, as well as means of eliminating them. For determination of the coefficient of thermal conductivity in insulation materials the comparative steady method is often employed, whereby no protective devices are used. In this case the thermal flow passes through the test specimen and through a control specimen with a known coefficient of thermal conductivity.

It has been established that the intermediate resistance between the contacting surfaces in materials with low thermal conductivity ($0.8 \cdot 10^{-3}$-$1.38 \cdot 10^{-3}$ cal/cm$\cdot$sec$\cdot$°C) shows up clearly in the results of the measurements. Experiments have shown that it is impossible to create an ideal contact, therefore special measures must be employed for calculating the gaps. The effect of gaps is accounted for in the method of F. Birch and A. Harri, in which an alternate chambers of the system of "heater-specimen-cooler" is employed in chambers of helium and nitrogen.

In other countries the divided bar method developed by A. E. Benfield is widely used to study the thermal conductivity of rocks. In this method the less-than-ideal contact between the specimen and the measuring system is taken into account.

The steady methods are able to determine only the coefficient of thermal conductivity, which is acknowledged as their main deficiency. The duration of the experiment and the inevitability of considerable redistribution of moisture in the investigated material make these methods difficult to use /55
for determining the thermophysical properties of moist materials. Other weaknesses of these methods are the time required to establish a steady state (3-8 hours), as a result of which a migration of moisture (if the rock specimens are moistened) may take place with even minimum temperature drops, and the difficulty of realizing a good contact between the specimen and the heater or cooler.

Despite these drawbacks, the methods of steady thermal flow are widely used for determining the thermal conductivity of structural and insulation materials in rock, and the majority of data in the literature pertaining to the thermophysical characteristics of various substances were obtained with their help. This is explained by the fact that, in the first place, of all the existing methods for determining thermal conductivity these are the most precise (experimental error does not exceed 3-5%), and, in the second place, the dimensions of the test specimen may be small. These methods are especially widely used for determining the coefficient of thermal conductivity for materials in the case of large absolute temperature values (Kozak, 1955).

Methods of Variable Thermal Flow

Among the methods of variable thermal flow an important place is occupied by the methods of the regular regimen proposed by G. M. Kondrat'yev (1954) and his students. A regular regimen is a process of heating or cooling of bodies, during the course of which the temperature distribution being established within the body does not depend on the initial conditions, is described by the exponential and determined by the form and dimensions of the body and by the temperature at its boundaries.

If a graph is constructed and the cooling off time of the body is plotted along the abscissa and the natural logarithm of the temperature difference of the body and the medium is plotted along the ordinate, then after the regular regimen has set in the graph of cooling off will represent a straight line.

In the stage of a regular regimen $t_x - t_o = Ae^{-m\tau}$, where t_x is the temperature at the tested point of the test material; t_o is the temperature of the ambient medium, assumed to be constant; τ is the time; m is the rate of change of the body's temperature; and A is a factor which depends on the geometirc form of the specimen and the coordinates of the point under /56
consideration.

If the Bio criterion is large (Bi > 100, for example, in cooling a body in a vigorously agitated fluid at constant temperature), then the coefficient of thermal conductivity is found by the simple equation $a = \Phi m$, where Φ is the form-factor. When Bi = const., if the coefficients of thermal diffusivity and thermal exchange α are known, and also the rate of temperature change of the body is found, the coefficient of thermal conductivity λ can be determined from the equation $\lambda = ac\gamma$, where a is the coefficient of thermal diffusivity; c is the specific thermal capacity; and γ is the volumetric weight.

Methods for determining the thermal diffusivity, thermal conductivity, and thermal capacity were proposed by G. M. Kondrat'yev. In his terminology they are the methods of a-calorimeter (for measuring thermal diffusivity), λ-calorimeter (for measuring thermal conductivity), and bi-calorimeter (for measuring the thermal conductivity and thermal diffusivity of thin plastics, insulation materials).

Lambda-calorimeter, alpha-calorimeter, and bi-calorimeter are hollow metal envelopes with hard rubber tubes and thermocouples in them. Inside the envelope is a metallic core, and the space between the core and the envelope contains the material to be investigated. The calorimeter is pregraduated, filled with the test material and cooled in a medium with a constant temperature when $a \to \infty$. The temperature of cooling m and then the coefficient of thermal conductivity for the test specimen are determined according to the cooling graph.

In comparison with the steady state methods, the regular regimen requires a shorter experiment time and permits the analysis of moist materials within small temperature limits, while the instruments are of comparatively simple construction. The accuracy of the coefficient of thermal conductivity determined by these instruments is 4%, and that for the coefficient of thermal diffusivity is 1.5%.

But measurement of the thermophysical coefficients by the regular regimen method has its weaknesses: a) it is difficult to achieve uniform filling of the instrument with the test material, which may cause disturbance of the heat exchange and errors in the determination of the thermophysical characteristics; b) it is impossible to determine all the coefficients (λ, c, a) in one /57 experiment; c) the regular regimen of cooling begins only after a long period of time for some materials (specimens with low thermal conductivity); d) the temperature gage must be placed within the test material, which may cause mechanical disturbance and distortion of the thermal field.

The quasi-steady state methods (in this case the temperature at any given point of the system being investigated is a linear function of time) permit measurement of all the thermophysical coefficients in one experiment (Lykov, 1952, 1956b; Semenov, 1955). This possibility, as well as the short duration of the experiment, are the main virtues of these methods. The drawback of the quasi-steady state methods is the necessity for complex apparatus to maintain the linear rate of temperature rise in the medium.

The methods based on the principles of a variable thermal field were first realized by Angstrom (Karslou, 1947). These methods reflect most objectively the variability of the thermal regimen of various natural objects with time and require the creation of a temperature wave on the surface of the specimen. Like the quasi-steady state methods, they permit determination of all three thermal parameters at one time, and require short experiments with comparatively small gradients in the test specimen (this determines their applicability to moist materials). But in contrast to the quasi-steady state methods, these experiments do not require complex equipment and the instruments employed are quite simple. Among the methods of this group are:

a) comparative methods of thermal similarity, based on heat exchange between the test specimen and a standard specimen having a different temperature at the start of the experiment (heat exchange takes place only by thermal conductivity). Weaknesses of these methods are: the necessity for rating the standard specimen and its storage, the possibility of determining only one coefficient -- the thermal conductivity, and the complexity of realizing in practice complete similarity of specimen and standard;

b) methods creating linear temperature changes on the test specimen surface (Lykov, 1952 and others). They make it possible to measure two /58 thermal characteristics of solid materials -- thermal diffusivity and conductivity -- and may be applied to bodies of any form.

The probe methods also belong to this group. They are based on study of the initial stage of development of a variable thermal field. The essence of these methods is determination of the temperature changes in heat sources (probes) or in changes in the amount of heat absorbed or given off by these probes in the period during which they are in the medium being studied. In various modifications of the probe methods, momentary, isothermic, or constant intensity heat sources are employed. In form the probes are: 1) laminar (plates with internal electric heaters), 2) cylindrical (rather long metallic rods of small cross section with internal momentary, isothermic, or constant intensity heat sources), or 3) spherical (a metallic sphere with internal heat source).

For determination of the thermal characteristics of structural materials A. M. Butov (1955) proposed the method of a linear plane heat source of constant intensity acting over a finite segment of time and consisting of finding the relationship of temperature to time for points located at one or another distance from the heat source. Also interesting are the probe methods worked out by A. F. Chudnovskiy (1954) and his coworkers. One of these is the impulse method proposed by Ye. Ye. Vishnevskiy, which permits measuring the thermal characteristics of moist specimens of rock, structural materials, and dispersed materials in air and in a vacuum at temperatures from -100 to +100 °C. The heat source is located within the body.

The advantages of the variable thermal regimen methods are that they are simple and no great amount of time is required for determination of all three thermal characteristics, thanks to which the natural moisture and temperature regimens do not have time to become disturbed.

At the same time the variable methods have important weaknesses: 1) in some of their modifications the test specimen is cut into two or three parts in order to place the heat source and thermometer inside it, and fitting and seating them one against the other disturbs the natural structure of the material; and 2) no correction is made for the heat content of the heaters or thermometers, which requires changing the procedure of the experiment when different heaters are employed. /59

Let us dwell in somewhat more detail on one of the variable methods.

A method was worked out by the Geothermy Laboratory of the O. Yu. Shmidt Institute of Earth Physics (Lyubimova et al., 1964 b) which utilizes the principles of heat convection from a momentary linear source (Tikhonov, Samarskiy, 1953). The theoretical bases of the method are: an infinitely long, thin heater rod is located in an inorganic solid medium, the temperature of which is constant at the moment its heat is communicated. At some moment of time $\tau = 0$ the rod is communicated a thermal impulse, following which the rod cools off. The temperature distribution from such an impulse has the form

$$T = \frac{Q_0}{4\pi kr} e^{-\frac{x^2+y^2}{4k\tau}},$$

where $x^2 + y^2 = r^2$ (r is the distance from the heater's surface to the point where the disturbance is recorded); T is the temperature produced by the momentary heat source having an intensity Q, located along an axis Z; in this case $Q = Q_0 c\rho$ which is the amount of heat given off by one unit of length of the source. Following substitution we have

$$T = \frac{Q}{4c\rho\pi kr} e^{-\frac{r^2}{4k\tau}}.$$

With maximum conditions

$$\left.\frac{dT}{d\tau}\right|_{\tau=\tau_m} = 0$$

we obtain

$$k = \frac{r^2}{4\tau_{max}} \text{ and } T_{max} = \frac{Q}{\rho c\pi r^2} e^{-1}$$

or /60

$$\rho c = \frac{\frac{Q}{T_{max}} e^{-1}}{\pi r^2}.$$

Consequently, to determine the thermal conductivity and thermal capacity of the test specimen it is sufficient to measure the distance between the instruments r, current I strength, the voltage on the heater winding V, the maximum change in temperature T_{max} at the point of measuring, and the maximum time τ_{max} required for the temperature at the point of measurement to reach its maximum value.

Certainly, it is impossible to achieve in practice the mathematical condition of an infinitely long and thin heater, which, in itself, introduces a certain amount of error into the experimental results; in addition, the authors of the method interpolate empirical corrections for the various distorting factors (the heterogeneity of the medium as the result of insertion of the instruments, the possibly less-than-ideal contact between the heater and the rock, etc.).

The investigations made by G. N. Starikova led to the conclusion that this method, with empirical corrections for the non-ideal arrangement of the experiment, permits reliable determination of the three thermal characteristics in one short experiment and on one core sample without disturbing the natural state of the specimen. The weakness of the method consists in the necessity that the test sample have a diameter of no less than 7.5 cm with r = 1.5 cm.

Comparing the methods described for determining the thermal characteristics, it is difficult to give preference to any one of them. It is desirable to investigate the test samples by several methods in order to obtain the most reliable data through correlation. The results of measurements made by several methods, of steady-state and regular regimens by the method of thermal similarity for example, show sufficient agreement between them (the disagreement does not exceed 5-6%). The choice of one or another method is often determined by such qualities as its applicability under given conditions to the material to be investigated, or its convenience and simple arrangements, rather than by its accuracy.

Experimental Study of the Thermal Conductivity of Rock /61

We determined the thermal conductivity of rock basically by the steady-state thermal field method. The investigation was repeated by the regular regimen method for a large number of samples from different regions and deposits. In this connection, for small diameter specimens, as usually are core samples drawn from great depth, we did not apply the usual a-calorimeter method since, in those cases, it is difficult to secure the necessary amount of heat emmission. These we investigated by the regular regimen method for specimens of small dimensions (Begunkova, Kissin, 1965). Accuracy of determination in both cases is 5-10%. Comparison of the results from the two methods gives good convergence (the difference is not more than 5-15%).

We studied the thermal conductivity of rocks from the fields of Russkiy Khutor, Yuzhno-Sukhokumskaya, Bazhigan, Stepnaya, Solonchakovaya, Gasha, Izberbash, Makhachkala, Karaman, Sulak, Babayurt, and Kaspiysk. A total of 125 samples was investigated. The values obtained for the coefficients of thermal ocnductivity in the air-dried state lie completely within the limits of variability of the values presented in the literature.

Preparation of the samples for study. Application of the steady-state thermal field method requires adherence to a number of conditions: precise seating of the specimens, very good contact between them and the sources of heat and cooling, avoidance of secondary heat dispersion, etc.

Thin plates were cut from the core samples by a rock saw and the plane surfaces were polished on a polishing wheel with abrasive powders to a thickness of 4-5 mm. With careful polishing the necessary condition of perpendicularity of the plane surfaces to the core axis was maintained.

The diameter of the specimens may vary within narrow limits when the constant ratio of diameter to thickness is maintained. After polishing, the specimens were covered with a thin coating of shellac or bakelite varnish to prevent moisture loss at the time of measurement as well as absorbtion of Vaseline by the specimens (to improve contact between the heaters and specimens, the latter were smeared with a thin layer of Vaseline). Special studies conducted to clarify the effect of varnish and Vaseline on the /63 accuracy of the experiments indicated that the application of such coatings considerably improved the mechanical contact.

/62

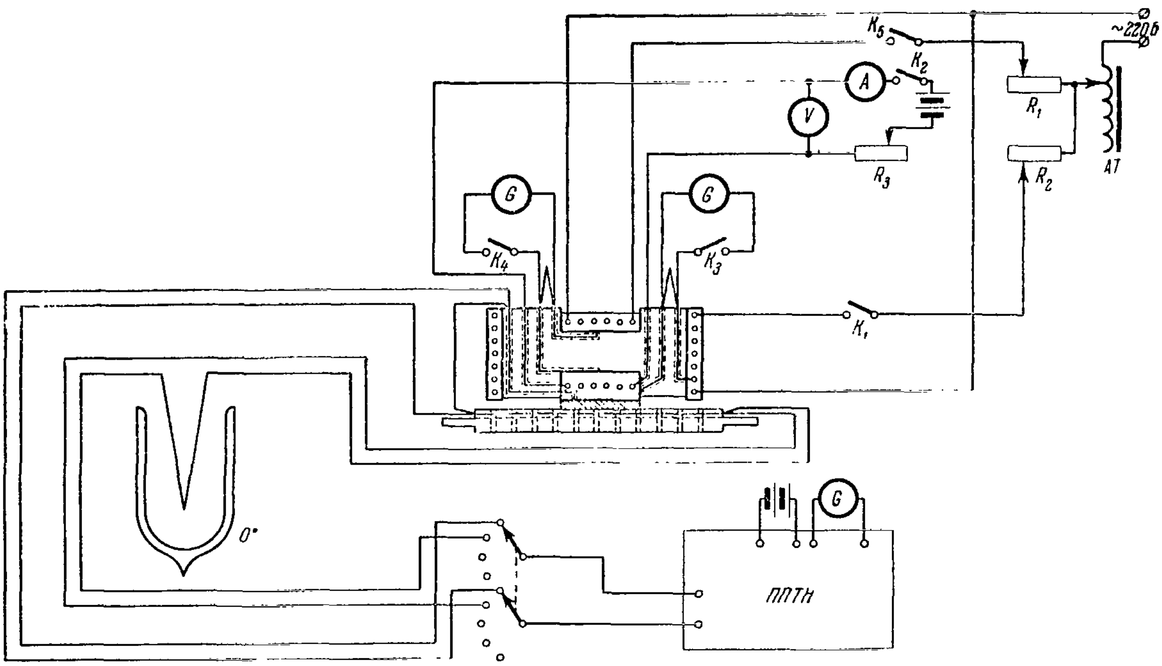

Figure 17. Schematic of set-up for determining thermal conductivity by the steady-state thermal field method.

0°, thermostat with 0° temperature; PPTN, low resistance potentiometer; G, mirror galvanometer; K_1-K_5, switches; R_1, R_2, R_3, rheostats; AT, autotransformer; A, ammeter; V, voltmeter.

We attempted to determine the actual thermal conductivity of the samples by calculating their moisture loss in transport. To do this, we measured the thermal conductivity of the dessicated sample to start with, and then that of the sample saturated with water. It would seem that in evaluating the coefficients of thermal conductivity, it would make sense to take into consideration the corrected coefficients obtained in such a manner, but, at the same time, the actual thermal conductivity of the core sample should be calculated with the help of an accepted model of the structure and porosity of the specimen, as was correctly suggested by Boldizar (1965).

Methodology of thermal conductivity determination. In investigation by the steady flow method, a flow of constant intensity is passed through the sample; one plane surface of the plate is heated, the other is cooled, in such a manner as to maintain a constant temperature drop between them. In other countries this method is called the "divided bar method." The general plan of the set-up is given in Figure 17, and the design of the assembly in which the specimen is placed is given in Figure 18.

The steady thermal flow from the "hot" to the "cold" plate through the test specimen (from details 5 of Figure 18 through 9 to 10) is established over 4-6 hours. The intensity of the thermal flow is calculated by measuring the voltage and current in the winding, heating the "hot" plate with the help of MBA-47/5 instruments. The heater coils are supplied with current from a bank of storage batteries. Lateral heat loss is eliminated with the help of protective (lateral) and auxiliary (upper) heaters which are powered by alternating line current through an LATR-2 autotransformer. Compensation of the lateral heat loss and establishment of a steady-state is checked by means of two differential thermocouples attached to M-17/1 and M-21/4 mirror galvanometers with a sensitivity of $2 \cdot 10^{-9}$ and $7.5 \cdot 10^{-9}$ A, respectively. The emf of the thermocouples is determined by a PPTN-1 low resistance potentiometer. The thermocouples are made of 0.015 mm diameter copper and constantan wires. The constant temperature of the cold plate of the cooler is maintained by an ultrathermostat. The coefficient of thermal conductivity λ is determined by the formula $\lambda = (Qx)/(S \cdot \Delta T)$, where Q is the thermal flow through the sample, equal to $0.24\ I^2V\tau$; x is the thickness of the sample; S is the area of the sample; ΔT is the temperature difference between the heater and cooler. /65

The apparatus used in our measurements was equipped with two devices which considerably modified its application: a device creating the necessary pressure, and another transmitting this pressure to the test specimen.

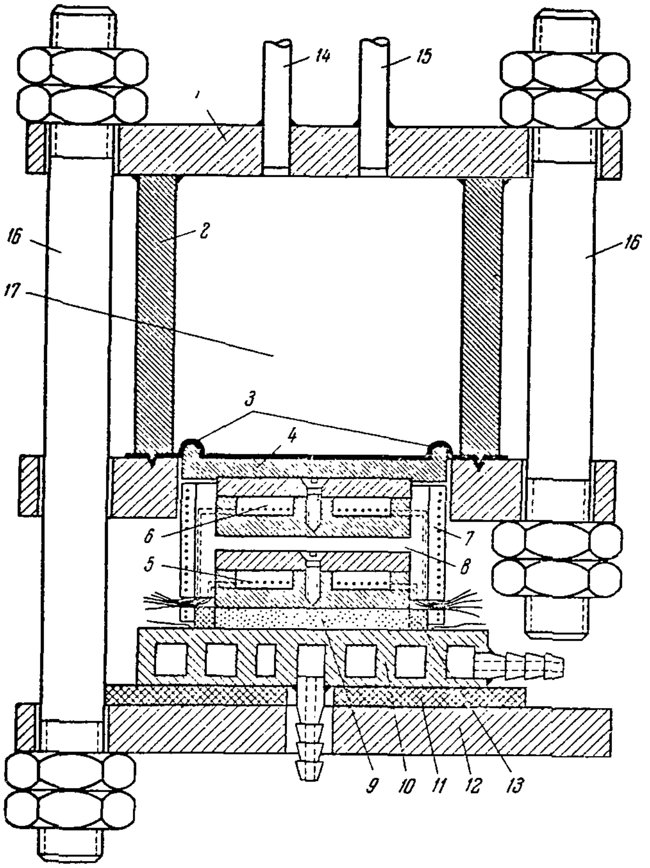

Figure 18. Design of the device in which the test specimen is placed for determination of the thermal conductivity by the steady-state thermal field method.

1, Top cover; 2, walls of the chamber in which supplementary pressure is created; 3, membrane which transmits the pressure to the test specimen; 4, moveable cover which transmits pressure to the test specimen; 5, main heater; 6, supplemental heater to eliminate heat loss through the main heater cover; 7, external heater to eliminate lateral heat loss from main heater; 8, double textolite holder for mounting main and supplemental heaters; 9, specimen being tested; 10, cooler which removes heat from the test specimen; 11, textolite cushion; 12, bottom cover; 13, ebonite collar to prevent lateral heat losses from the specimen; 14, pipe to force pump; 15, pipe to manometer; 16, bolts holding the upper and lower covers together; 17, oil pressure reservoir.

The first device is a hydraulic jack from which the lifting mechanism has been removed; it supplies oil under pressure to the reservoir of the apparatus (in Figure 18, only the outlet to it is shown -- component 14). The second device, for transmitting high pressure to the test speciment, consists of a pressure chamber (component 17 in Figure 18), a flexible, shaped membrane of sheet copper (3), and a moveable cover (4). The top of component 4 has the same form as the shaped membrane and thereby receives almost all the pressure arriving on the membrane, preventing damage to the latter. The diameter of the upper portion of component 4 is larger than that of the lower, which creates a greater pressure on the test specimen than is in the pressure chamber (proportional to the ratio of the squares of the radii). The mobility of the membrane is sufficient to compensate for the deformation of the test specimen and to transmit all the pressure to the test specimen, even when the experiments are of insignificant duration. The pressure is measured by the manometer readings (the outlet to it from the pressure reservoir is shown, component 15 of Figure 18) and by the ratio of the radii.

During measurement in the laboratory, rocks are usually under conditions quite different from the natural ones: first of all is the absence of the formational pressure. Construction of such design additions makes it possible to measure the thermal conductivity of rocks at various pressures (from 1 to 280 atm in out chart). The results of such experiments which we made are presented in Figure 19. Development of the device made it possible to establish the necessary corrections for the pressure, which were introduced into the calculation of the thermal conductivity of the test sample. It must be noted that, on the whole, the changes in thermal conductivity of rocks in relation to pressure have obviously not been clearly understood. This problem requires special analysis and must be an object of further study. We used the supplemental design features of the apparatus basically for other purposes. It is known in the literature that the weakness of the steady state method is the difficulty of achieving good mechanical contact between the /66 test specimen, cooler, and heater. We eliminated this difficulty by using the supplemental devices, which helped to create an excellent contact between the specimen and the heaters.

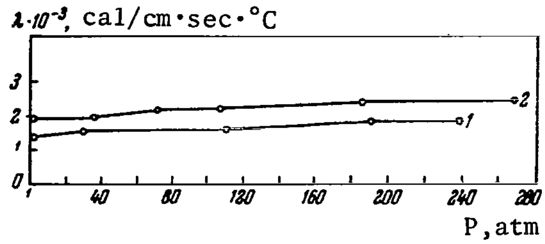

Figure 19. Thermal conductivity of clay in relation to pressure.

1, first sample; 2, second sample.

Results of Determination of Thermal Conductivity of Rocks

The results of determination of the thermal conductivity of 125 rock samples from the region studied, taking all corrections into account, are completely within the limits of variations given in the literature for this parameter. The relatively small magnitude of some of the individual thermal conductivity values in our determinations, in comparison with the published data, is possibly explained by allowance for temperature corrections.

The clays have the lowest thermal conductivity values in the region studied (Table 9). They vary from 1.84 to 4.51 mcal/cm·sec·°C for the Sarmatian deposits, from 2.04 to 4.73 for the Chokraksk, from 1.56 to 3.96 for the Pliocene, and from 3.21 to 3.78 for the Mesozoic deposits. The compaction of the argillaceous rocks with depth leads to a considerable increase in their thermal conductivity. The upper limits of thermal conductivity for the Sarmatian and Chokraksk clays are increased with an increase in their sand content.

The sandstones and aleurolites have the highest thermal conductivity.
Their thermal conductivity varies within broad limits, depending on the /73
composition of the detrital material (the dense quartzitic sandstones have the highest).

Thermal conductivity of the limestones varies from 3.00 (for writing chalk) to 6.56 mcal/cm·sec·°C.

In Table 10 data are given on the thermal conductivity of individual lithographic varieties of rock. Each value for the thermal conductivity is the average of five to eight determinations for one sample, and in the case of lithologically heterogenous intervals the average value for this interval is the weighted mean, taking into account the thickness of the rocks which are components of the interval in question.

TABLE 9. THERMAL CONDUCTIVITY OF SEDIMENTARY ROCKS IN DAGESTAN, 10^{-3} cal/cm·sec·°C

Rocks	Age	No. of deter-min.	Author's data			Data by G.M.Sukharev et al., (1960)			Data by I.G. Kissin (1964)			F.Birch, Sherer, Spicer, (1949)	
			λ_{min}	λ_{max}	λ_{avg}	λ_{min}	λ_{max}	λ_{avg}	λ_{min}	λ_{max}	λ_{avg}	λ_{min}	λ_{max}
Clays	N_2	63	1,56	4,73	3,47								
	N_1 srm		1,56	3,96									
	N_1 tsh		1,84	4,51		2,67	3,42						
	Pg_3 mkp		2,04	4,73	3,38								
	Mz				3,73	3,27	3,79		3,28	3,47			
			3,21	3,73	3,72								
Argillites	Cr_1	4	3,48	3,36									
	N_1 srm	33	3,69	8,93	5,60							2,50	10,30
	N_1krg + tsch		4,27	6,72				7,80					
	Cr_2		3,69	6,72									
Sands, Sandstones											5,95		
	Cr_1		5,06	8,91				5,45	6,75				
			5,85	7,88									
Limestones	J	13	3,00	6,56	5,84	4,32	7,40				2,00	6,00	
	Cr							5,60	7,08				
Aleurolites	Pg_2	7						4,83	5,04				
	Cr_2									6,45			
Dolomites	$Cr_1 - I_1$		3,64	7,88									
	$Cr_1 - I_8$		3,87	6,62									

Note: Commas indicate decimal points.

/67

TABLE 10. RESULTS OF DETERMINATION OF THE THERMAL CONDUCTIVITY OF ROCKS OF SEDIMENTARY COVER IN VARIOUS DAGESTAN AREAS

No. of well	Depth of core sample in meters	Age of rock	Lithologic composition	Thermal conductivity, mcal/cm•sec•°C
			Yuzhno-Sukhokumskaya	
4	3,140-3,146	Cr_1	Aleurolite: argillaceous, glauconitic, quartzitic, slightly calcareous	4.62
	3,150-3,154	"	Sandstone: glauconitic, quartzitic, slightly calcareous	5.52
	3,302-3,308	"	Sandstone: slightly calcareous	6.019
	3,315-3,323	"	The same.	6.695
	3,447-3,450	I_3	Dolomite: argillaceous	6.62
	3,701-3,706	I_2	Sandstone: quartzitic feldspatic	5.85
11	2,545-2,550	Cr_2	Dense limestone with thin interstratifications of arenaceous, calcareous clays	5.59
	2,655-2,660	"	Clays: bedded, dense, calcareous	3.65
11	3,125-3,130	Cr_1	Aleurolite: argillaceous	4.78
	3,403-3,410	I_3	Clay: bedded	3.73
	3,593-3,597	I_2	Clay: non-calcareous	3.211
8	1,999-2,007	Pg_3 mkp	Clay: carbonaceous	3.78
	3,312-3,318	Cr_1	Limestone: detrital, arenaceous	3.95
			Russkiy Khutor	
11	2,457-2,462	Cr_2	Limestone with thin interstratifications of calcareous clays	4.25
	2,457-2,462	Cr_2	White, friable limestone (writing chalk)	2.999
	2,446-2,651	Cr_1 al	Sandy-aleurolitic rock, dense, glauconitic	5.72
	2,651-2,656	"	" " " "	6.436
	3,192-3,202	Cr_1 b	Sandstone: slightly calcareous	5.096
	3,211-3,219	Cr_1	Sandstone: slightly calcareous	5.33
	3,259-3,265	Cr_1 h	Sandstone: calcareous	5.343
4	3,044-3,046	Cr_1 ap	Sandstone: calcareous, glauconitic, Quartzitic, fine and coarse grained	5.097
2	3,390-3,395	I_2	Aleurolite: dense	6.019

TABLE 10. (Continued)

No. of well	Depth of core sample in meters	Age of rock	Lithologic composition	Thermal conductivity, mcal/cm·sec·°C
			Bazhigan	
2	3,906-3,911	I_1	Tuffogenic sandstone	4.45
3	3,996-4,000	"	Tuffogenic aleurolite	3.64
			Stepnaya	
1	2,893-289	Cr_2	Limestone: white and gray, dense	4.74
	2,929-2,935	"	" " " " "	5.49
			Solonchakovaya	
1	3,429-3,434	Cr_1	Sandstone with glauconitic-hydromicaceous and carbonaceous cement	8.905
	3,434-3,439	"	Aleurolite: coarse & fine grained	3.77
	3,670-3,675	I_3	Aleurolite: quartzitic	5.057
	3,681-3,686	I_2	Sandstone: quartzitic	7.878
	2,908-2,915	Cr_2	Clay: carbonaceous	3.412
	2,915-2,921	"	Limestone: dense	4.97
	2,915-2,921	"	Clay: carbonaceous	2.33
3	2,930-2,935	Cr_1 b	Limestone: arenaceous	3.81
	3,444-3,448	Cr_1	Limestone: gray, fine grained, with sand-aleurolitic-argillaceous impurities	6.565
	3,535-3,540	"	Argillite: aleurolytic with abundant pyrites	3.90
	3,535-3,540	"	" " "	4.36
	3,552-3,558	"	Dolomite: fine & coarse grained	3.87
	3,552-3,558	"	" " " " "	4.564
	3,535-3,540	"	Argillite: aleurolytic with abundant pyrites	3.484
			Gasha	
29	2,130-2,137	Pg_3	Limestone: argillaceous, fine grained, badly crumbled	4.745
	2,672-2,677	Cr_2	Limestone: aleurolitic-argillaceous fine grained with pyrite granules	5.72
	2,970-2,974	Cr_2 m	Limestone: argillaceous, fine grained, badly crumbled	3.204
29	2,970-2,974	"	The same	4.693
	3,140-3,146	Cr_1	Sandstone	3.562

TABLE 10. (Continued)

No. of well	Depth of core sample in meters	Age of rock	Lithologic composition	Thermal conductivity, mcal/cm·sec·°C
			Sulak	
25	308-309	Na_2apsh	Arenaceous clay	1.99
	519-528	Na_2 ak	" "	2.15
	773-780	"	" "	2.67
	773-780	"	" "	2.34
	800-810	"	" "	2.97
	878-883	"	" "	1.92
	951-961	"	" "	1.56
	1,207-1,215	N_1 mt	" "	1.65
			Babayurt	
55	519-529	N_1 srm	Clay	3.675
			Karaman	
	108-113	N_2	Clay: gray, calcareous	2.79
	185-310	"	Clay: gray, calcareous, aleurol.	2.475
	308-316	"	" " " "	2.208
	333-393	"	" " " "	1.57
Temirgoe-	403-408	"	Clay: calcareous, aleurolytic	3.06
explora.	428-444	"	" " "	3.114
	701-707	N_2 ap	Clay: dense,calcareous,aleurolytic	3.06
	707-709	" "	" " " "	2,835
	757-774	" "	" " " "	3.42
	816-834	" "	" " " "	3.25
	1,003-1,013	" "	" " " "	3.28
	1,500	N_2 ak	Clay: calcareous with interstratifications of aleurolites	3.96
	1,919	N_1 m	Sandstone: argillaceous marly with sparse pebbles	3.63
	2,000	"	The same	3.643
	2,442-2,453	"	The same	3.81
Terminal	2,817-2,820	N_2 srm	Clay: slightly arenaceous, micaceous, bedded, dense	2.80
	2,900-2,905	"	Clay: micaceous with deposits of sand and interstratifications of aleurolite	3.18
1 (terminal)	3,059-3,064	N_1 srm	Clay: micaceous	1.99

TABLE 10. (Continued) /71

No. of well	Depth of core sample in meters	Age of rock	Lithologic composition	Thermal conductivity, mcal/ cm•sec•°C
1 (terminal)	2,867-2,872	N_1 srm	Sandstone: quartzitic	6.37
	2,867-2,872	"	Clay: arenaceous	3.94
	2,900-1,905	"	Clay: micaceous, thinly bedded, with aleurolite interstratification and sand deposits	3.03
	2,956-2,961	"	Clay:micaceous,dense,thinly bed	3.95
	3,116-3,120	"	Sandstone: micaceous, dense	6.72
	3,158-3,162	"	Clay: arenaceous,micaceous, dense, thinly bedded	4.51
	3,220-3,234	"	Argillaceous sandstone	5.018
	3,260-3,264	"	" "	4.29
	3,303-3,306	"	" "	4.22
	3,701.5-3,705	"	Sandstone: quartzitic, feldspatic, hard, bedded	5.24
	4,003-4,008	N_1 krg	Sandstone: fine,close grained	5.317
	3,388-3,390	N_1 srm	Clay: strongly arenaceous, bedded	3.83
	49	Q_1	Clay	2.42
	3,007-3,012	N_1 srm	Clay: dense, close grained	2.78
			Makhachkala	
215	1,434-1,437	N_1 tch	Clay	3.348
	1,503-1,508	"	Clay	2.041
	1,503-1,508	"	Sandstone:water-bearing	4.368
	1,608-1,683	"	Clay with interstratifications of marl	3.270
	1,680-1,683	"	Clay with interstratifications of marl	3.536
			Izberbash	
235,237	546.5-582	N_1 srm	Argillaceous sandstone	4.27
	1,215-1,220	N_1 tch	Sandstone:fine grained with interstratifications of clay	4.07
	1,520-1,524	"	Sandstone:fine grained, friable, with interstratifications of clay	4.15
	1,728-1,735	"	Sandstone: bedded, dense, with interstratifications of clay.	5.12
	1,844.5	"	Sandstone: dense, with interstratifications of clay	4.17
	1,852-1,865	"	The same	4.93
	1,941-1,962	"	Sandstone: fine grained, dense, argillaceous	5.27

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TABLE 10. (Conclusion)

No. of well	Depth of core sample in meters	Age of rock	Lithologic composition	Thermal conductivity, mcal/cm•sec•°C
2-P	10	N_1^3	Clays with rare and thin interstratifications of marl and sandstones	1.849
	16	"	The same	2.68
	25	"	" "	2.75
	30	"	" "	1.836
	35	"	" "	3.21
	40	"	" "	1.975
	45	"	" "	2.349
	60	"	" "	2.52
	100	"	" "	1.80
	120	"	" "	2.30
	130	"	" "	2.36
	140	"	" "	2.24
			Kaspiysk	
2-T	1,296-1,307	N_1 krg	Sandstone: hard, fine grained, argillaceous, micaceous	5.668
	1,544-1,551	"	Aleurolite	5.668
	1,654-1,669	N_1 tch	Sandstone	4.602
	1,669-1,684	N_1^2 tch	"	5.603
	1,852-1,865	"	"	4.507
	1,420-1,429	N_1 krg	Clay with thin interstratifications of sandstone	3.718
	1,526-1,536	N_1 tch	Clay with interstatifications of sand and sandstone	3.432
	1,536-1,546	"	The same	3.463
	1,621-1,631	"	Clay: hard arenaceous	4.433
	1,732-1,734	"	Hard sandstone	5.668
	1,795-1,801	"	Argillaceous sandstone	3.687
	1,833-1,845	"	Arenaceous clay	4.732
	1,855-1,864	"	" "	3.471
	1,845-1,855	"	" "	2.925

CHAPTER V /74

DISTRIBUTION OF CONDUCTIVE THERMAL FLOW IN THE DAGESTAN TERRITORY

Determination of Conductive Thermal Flow and Accepted Methods of Calculation

Determination of the thermal flow yields the most complete information about the thermal state of the Earth, the study of which is necessary for the solution of many geological and geophysical problems. Statistical analysis of data concerning thermal flow is often applied to extremely unequally distributed experimental data, and to the extent that new information becomes available, the situation of the separate anomalies changes. Therefore determination of the thermal flow in different regions should define more accurately the general nature of the distribution of this parameter in large areas, for example in the entire area of the USSR.

The thermal flow observed at the Earth's surface, although it originates in the depths, is deformed in the lithosphere as a result of various geologic processes taking place in it, processes accompanied by the generation or absorption of thermal energy and also by a redistribution of heat by the movement of ground water. Evaluation of these, or other, factors' role in the formation of the natural thermal field of the lithosphere permits differentiation of the primary from the secondary ones among them.

Thermal flow is the product of two jointly determinable factors -- the temperature gradient and the thermal conductivity of the rocks: $q = (dT/dz)\lambda$. Obtaining reliable data concerning the thermal flow requires, therefore, precise measurements of both these quantities.

Evaluation of the true value of the thermal flow requires taking into account the possible distortions resulting from various man-made and natural /75
factors. The distortion of thermal flow in the drilling of wells belongs to the first group of factors, the circulation of ground water and the changes of climatic conditions belong to the second, as does the effect of topography,

all of which are missing in the laboratory analysis of data concerning the natural moisture and temperature of rock and the pressure under actual *in situ* conditions.

The effect of man-made factors was avoided in our investigations by calculating equivalent gradients and employing thermometric data from wells after a long period of idleness.

Correction for topography becomes very important in mountainous regions. Its effect may be positive or negative and must be evaluated for each individual case (Howard, Sass, 1964, and others). Examining the effect of topography on measurements of the thermal flow at the Earth's surface, Lachenbruch (1965) showed that the vertical temperature gradient, in the case of a slope, is overestimated in the lower part of the slope and understated in the upper part and beyond its borders. The effect of the relief's irregularity decreases with depth and in most cases does not exceed 1% at a depth of 500 m (Roy, 1963).

Methods also exist for evaluating distortions of the thermal flow as a result of climatic variations in recent periods of geologic history (G. Karsloy and D. Eger) and of rapid vertical tectonic movements and erosion (A. Benfield). These modifications require certain assumptions concerning the thermal processes.

The absence of any significant climatic changes during recent geologic history in the areas being studied, as well as the smooth nature of their surfaces permitted avoidance of the introduction of corrections for the effect of climate and relief. As for the effect of underground water, there are still no reliable methods for evaluating it; therefore the intervals investigated were selected at depths where the rate of water movement is insignificant and should not noticeably affect the temperature distribution, i.e., in the zones of limited and very limited water exchange. Special studies, and the application of correction coefficients existing in the literature (Roy, 1963) to the non-correspondence of moisture, pressure, and temperature of a sample under laboratory conditions and in the natural state, permitted the acquiring of reliable values for the thermal con- /76
ductivity of the rocks.

In the evaluation of the thermal flow for actual fields, weighted averages are implied by the "average" for the values of any of the determined parameters for the portion of the profile studied, averages obtained by estimating the thickness of the homogenous member in all cases where it seemed reasonable.

We determined the thermal flow along well shafts in twelve fields located in two tectonic zones of Dagestan. In the graphs cited below, the changes in the temperature gradient (γ), thermal conductivity of the rocks (λ), and thermal flow (q) in relation to depth are shown for each point investigated. Let us examine these results.

Results of the Determinations

Izberbash. Wildcat wells 235 and 237, and producing well 2-P, located in the Izberbash anticline (Maritime Plain of South Dagestan) were studied. This structure is located in the submerged portion of the dome of the Eastern anticlinal zone of the Kulsary-Divichinsk depression and has a northwest strike.

The Izberbash fold is a brachyanticline stretching from northwest to southeast, a large part of which is located beneath the Caspian Sea. The structure is box-like with a slanted dome and precipitous limbs. The amplitude of uplift is 400-500 m in different portions of the structure.

We studied two members of the profile. One of them, lying at the 10-140 m interval, was represented by water-impermeable gray bedded clays of the Sarmatian stage; the other, at the 1,216-1,962 m interval, was water-bearing sandstones of the Karagansk and Chokraksk horizons. Temperature gradients for the argillaceous member were determined by data from observations in the operating well, but for the sandstone member they were determined from the results of thermal logging (conducted after a month's stabilization) and taking spot measurements into the calculations. For the argillaceous member the temperature gradient was 0.034 °C/m, and for the sandstones it varied from 0.013 to 0.018 °C/m. When the corrections for moisture, which was up to 20% for the clays and up to 30% for the sandstones, were included in the calculations, the coefficients of thermal conductivity /77 were 2.32 for the clays and from 4.07 to 5.27 mcal/cm·sec·°C for the sandstones. The results of the determinations of temperature gradient, thermal conductivity, and thermal flow in the Izberbash field are given in Table 11 and Figure 20 for each interval of depth. The average thermal flow for the entire profile of the Izberbash field is 0.74 μcal/cm^2·sec.

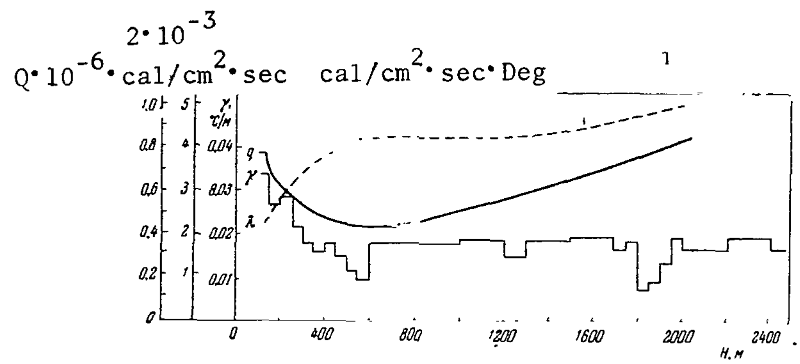

Figure 20. Changes in the temperature gradient (γ), thermal conductivity of the rocks (λ), and thermal flow (q) in relation to depth in the Izberbash anticline region.

The average value of the conductive thermal flow in the sandstone member is 0.69 μcal/cm^2·sec. In the clay member the average thermal flow in the 10-40 m interval is 0.78 μcal/cm^2·sec. At the same time, it is 0.81 in the 10-60 m interval and 0.75 μcal/cm^2·sec in the deeper lying (10-140 m) interval, which is somewhat nearer the value obtained for the sandstones. If the value of the thermal flow in the upper part of the argillaceous member corresponds to the steady-state thermal field, then the cause of the increase in thermal flow can be seen only in a supplemental emission of heat in the form of some type of exothermic processes taking place directly in this horizon. Still, the variations of the flow in this region could be caused by hydrogeological factors: there are many thermal sources known to exist in the environs of the Izberbash structure which are fed by waters of the Karagansk-Chokraksk deposits and discharge at the surface primarily in zones of fracture.

TABLE 11. RESULTS OF THE DETERMINATION, BY INTERVAL, OF THE TEMPERATURE GRADIENT, THERMAL CONDUCTIVITY, AND THERMAL FLOW IN THE VARIOUS REGIONS OF DAGESTAN. /78

Depth interval studied, in meters	Lithologic composition	Temp. grad., °C/m	Therm. cond., μcal/cm·sec·°C	Therm. flow, μcal/cm^2·sec	Remarks
		Izberbash			
10-60	Clays	0.034	2.27	0.81	
60-140	"	"	2.21	0.75	
10-140	"	"	2.32	0.78	Avg.of 2 determ.
1,216-1,220	Sandstones	0.015	4.07	0.61	
1,520-1,524	Sandstones	0.016	4.15	0.68	
1,723-1,735	"	0.016	4.12	0.82	
1,844.5	"	0.013	4.17	0.64	
1,852.8	"	0.016	5.93	0.75	
1,941-1,962	"	0.018	5.27	0.92	
1,216-1,962	"			0.69	Avg.of 6 determ.
		Makhachkala			
1,434-1,437	Water-bearing sandstone with interstratification of clays.	0.031	3.35	1.038	
1,503-1,508	The same	0.025	4.2	1.05	
1,677-1,683	The same	0.022	3.41	0.75	
		Gasha			
2,130-2,137	Gray limestones, aleuritic-argillaceous, micrograined, crumbled	0.018	4.74	0.854	
2,672-2,677	The same	0.019	5.72	1.075	
2,970-2,974	Clays	0.018	3.20	0.577	
2,970-2,974	Sandstones	0.018	4.69	0.845	
3,140-3,146	Clays	0.019	3.56	0.677	
		Kaspiysk			
1,420-1,429	Clays with interstratification of sand and sandstone	0.023	3.72	0.855	
1,526-1,536	The same	0.023	3.43	0.789	
1,536-1,546	" "	0.023	3.46	0.796	
1,621-1,631	Argillaceous sandstone	0.05	4.33	2.165	
1,732-1,734	Sandstone	0.03	5.7	1.7	
1,745-1,751	"	0.03	5.7	1.7	
1,795-1,801	"	0.03	3.9	1.11	
1,833-1,845	"	0.03	4.73	1.42	

TABLE 11. (Continued

Depth interval studied, in meters	Lithologic composition	Temp. grad., °C/m	Therm. cond., μcal/cm·sec·°C	Therm. flow, μcal/cm²·sec	Remarks
1,845-1,855	Arenaceous clays	0.03	2.92	0.878	
1,855-1,864		0.03	3.47	1.041	
	Karaman /79				
108-113	Alternation of gray, calcareous, aleurolitic, clays, sands, & weakly cemented water-bearing sandstones.	0.023	2.79	0.64	
285-310	The same		2.48	0.57	
303-316	" "		2.20	0.50	
383-393	" "		1.54	0.36	
403-408	" "		3.06	0.71	
428-444	" "		3.11	0.73	
408-444	" "		2.54	0.58	Avg.of 6 determin.
701-707	" "	0.024	3.06	0.734	
707-709	" "		2.84	0.68	
767-774	" "		3.42	0.82	
816-834	" "		3.25	0.78	
1,002-1,013	" "		3.28	0.79	
469-1,051	" "		3.17	0.73	Avg.of 5 determin.
1,500	Dense clays,calcareous with interstratification of limestones-coquina	0.025	8.96	0.99	Thermal flow values assumed typical for lithologically heterogeneous interval 1,051-1,698
1,919	Calcareous clays with interstratification of aleurolites and sandstones; in upper part of profile, argillaceous marls with occasional pebbles	0.027	3.68	0.98	
2,000	The same		3.64	0.98	
2,142-2,453	" "		3.81	1.021	
1,692-2,525	" "		3.70	0.99	Avg.of 3 determin.
2,817-2,820	Interbedding of weakly & strongly arenaceous clay	0.027	2.80	0.76	
2,867-2,872	The same	0.027	4.97	1.34	

TABLE 11. (Continued)

Depth interval studied, in meters	Lithologic composition	Temp. grad., °C/m	Therm. cond., μcal/cm·sec·°C	Therm. flow, μcal/cm²·sec	Remarks
		Karaman			
2,900-2,905	Interbedding of weakly & strongly arenaceous clays	0.032	3.18	1.02	
2,956-2,961	The same	0.032	3.95	1.26	
3,007-3,012	" "	0.04	2.78	1.11	
3,059-3,004	" "	0.04	1.99	0.80	
3,116-3,120	" "	0.025	6.72	1.68	
3,152-3,162	" "	0.025	4.51	1.13	
3,220-3,224	" "	0.031	5.02	2.06	
3,260-3,264	" "	0.031	4.29	1.33	
3,303-3,306	" "	0.026	4.22	1.10	
3,383-3,390	" "	0.023	3.33	0.77	
2,589-3,737	" "			1.20	Avg.of 12 determ.
3,701-3,705	Sandstone,gray & close grained, quartzitic-feldspatic hard, bedded, water-bearing	0.034	5.00	1.70	
4,003-4,008	The same	0.034	5.32	1.81	
		Sulak			
308-309	Clays with interstratification of sand & coquina	0.024	4.59	1.102	
519-523	The same	0.025	3.30	0.825	
773-780	" "	0.025	2.67	0.668	
800-810	" "	0.025	2.97	0.743	
878-883	" "	0.025	1.92	0.479	
951-961	" "	0.025	1.56	0.39	
1,207-1,215	" "	0.027	1.65	0.446	
		Russkiy Khutor			
2,457-2,462	Limestone,argillaceous-aleurolitic	0.33	3.62	1.19	
2,646-2,651	Sandstone,argellaceous-aleurolitic	0.029	6.03	1.76	
2,651-2,656	The same				
3,044-3,046	Argillaceous-aleurolitic member with interstratification of sandstone	0.023	5.06	1.16	
3,192-3,202	The same	0.020	5.10	1.02	
3,211-3,219	Argillaceous aleurolite	0.026	5.83	1.38	

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TABLE 11. (Concluded)

Depth interval studied, in meters	Lithologic composition	Temp. grad., °C/m	Therm. cond., µcal/ cm•sec• °C	Therm. flow, µcal/ cm^2• sec	Remarks
3,259-3,265	Argillaceous aleurolite	0.018	5.34	0.96	
3,310-3,315	Arenaceous-argillaceous aleurolite	0.020	5.08	1.02	
3,310-3,395	The same	0.029	6.02	1.74	
2,435-3,395	" "	0.026	5.08	1.32	Avg.of 8 determin.
	Yuzhno-Sukhokumskaya				
1,900-2,300	Argillaceous member	0.035	3.78	1.32	
2,500-2,750	Limestones	0.023	5.59	1.285	
3,100-3,200	Aleurolite-sandstone member	0.023	5.28	1.21	
3,290-3,340	Sandstones	0.023	5.32	1.22	
3,410-3,420	Clays	0.023	3.73	0.86	
3,420-3,464	Dolomites	0.023	6.62	1.52	
3,570-3,620	Aleurite-argillaceous member	0.023	3.21	0.74	
3,620-3,730	Argillaceous sandstones	0.023	5.85	1.35	
	Solonchankovaya				
2,600-2,950	Interbedding of carbonaceous clays and limestones	0.025	3.40	0.85	Average of determinations
3,422-3,444	Sandstone with interstratifications of aleurolites	0.017	6.12	1.06	Average of 2 determinations
3,444-3,530	Arenaceous limestone	0.017	6.56	1.14	
3,530-3,622	Dolomite with interstratifications of aleuritic argillite	0.017	4.05	0.70	Average of 5 determinations
3,622-3,735	Quartzitic sandstones and aleurolites	0.018	6.47	1.14	Average of 2 determinations
	Stepnaya				
2,929-2,935	Sand-aleurite member	0.025	5.486	1.37	
2,829-2,898	" " "	0.025	5.044	1.26	
	Bazhigan				
Well No.3 3,996-4,000	Tuffogenic aleurolite	0.036	3.64	1.31	
Well No.2 3,906-3,911	Tuffogenic sandstone	0.042	4.45	1.87	

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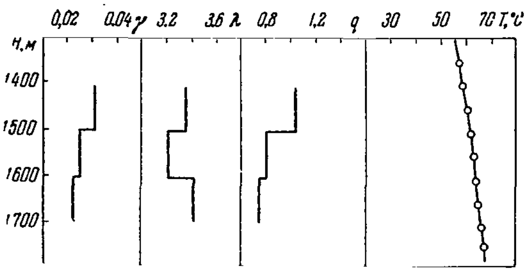

Figure 21. Changes in temperature gradient (γ), thermal conductivity (λ), and thermal flow (q) in relation to depth in the Chokraksk deposits of the well Makhachkala-215.

Makhachkala. This structure is located in direct proximity to Mt. Makhachkala between the Terkitau mountains and the Caspian Sea. It is in the form of a brachy-anticline, stretched out over 8 km from northwest to southeast with a maximum width of 2 km. Its axis dips 2-3° toward the southeast and 4-5° to the northwest. Amplitude of uplift is 340 m. /82

We investigated well No. 215. Its working surface is at the 1,800 m mark in the Chokraksk deposits represented by alternating water-bearing sandstones and clays. The investigated interval (1,400-1,700 m) is represented by waterbearing sandstones with interstratifications of arenaceous clays. Two thermograms were taken along the shaft. The stabilization period before the second thermogram (2 months) proved to be sufficient to achieve stable temperature values, which was checked by the "dual thermogram" method. Gradient values in the given interval vary from 0.22 to 0.031 °C/m. Taking into account the corrections for moisture, pressure, and temperature, the coefficients of thermal conductivity determined vary from 3.35 to 4.2 m/cal cm·sec·°C.

The results of the determination of thermal flow by interval for the Makhachkala field are given in Table 11 and Figure 21. The average thermal flow is 0.96 μcal/cm^2·sec in the Chokraksk deposits of the Makhachkala field.

Gasha. This structure is confined to the western anticlinal zone of the Kulsary-Divichinsk depression and is situated between the uplifts of Saltabaye on the north and Selli on the south. Cenezoic and Mesozoic rocks are involved in its geologic structure. It is a narrow, box-like fold with /83
a sloping dome and relatively steep, somewhat asymmetrical limbs.

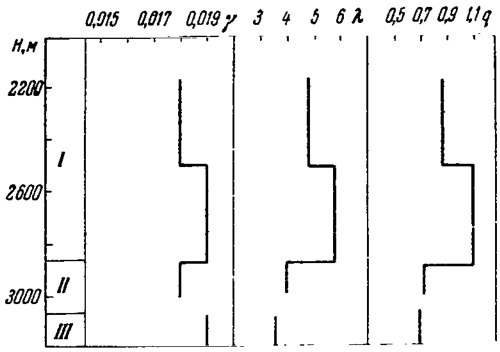

Figure 22. Changes in temperature gradient (γ), thermal conductivity (λ), and thermal flow (q) in relation to depth in the Gasha field (Well No. 29).

I, upper cretaceous; II, lower cretaceous; III, Jurassic.

Well No. 29 was studied here. The intervals investigated were 2,130-2,677 m, composed of Cretaceous limestones, and 2,970-3,146 m, corresponding to the sand-clayey member of the Jurassic deposits. The temperature gradients were determined from analysis of thermal logs of the given well and spot measurements of deep temperatures made in this field. The gradient values are almost constant for the portion of the profile studied, 0.018-0.019 °C/m.

Taking into account the corrections for moisture (the rocks, although dense, were badly fractured), pressure, and temperature, coefficients were obtained for the thermal conductivity of the rocks comprising the investigated intervals. The range of measurements for the thermal conductivity was from 3.20 (for clays) to 5.72 μcal/cm·sec·°C (for limestones). The average thermal conductivity for the profile was 4.95 μcal/cm·sec·°C. The results are given in Table 11 and Figure 22 for the determination by interval of the geothermal parameters of Well No. 29. The weighted average of conductive thermal flow here is 0.87 μcal/cm^2·sec.

<u>Kaspiysk</u>. This exploratory area is located 18 km south of the Makhachkala field. Tectonically it is confined to the northeastern sloping /84
limb of the Talginsk uplift.

The thermal flow was determined in well No. 3-T, the working surface of which is located at a depth of 1,900 m in Chokrakak aquiferous sandstones. The intervals studied are composed of sandstones and arenaceous clays of the Karagansk (1,400-1,546 m) and Chokraksk (1,631-1,864 m) deposits. Stable gradients of temperature were determined by spot measurements made in the

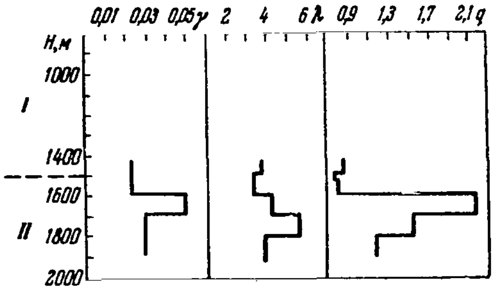

Figure 23. Changes in the temperature gradient (γ), thermal conductivity (λ), and thermal flow (q) in relation to depth in the Kaspiysk field (Well No. 3-T). I, Karagansk horizon (arenaceous clays); II, Chokraksk horizon (sandstone with interstratifications of arenaceous clays).

well following a month of idleness. The values varied from 0.023 to 0.05 °C/m. Calculating in the corrections for moisture and temperature of the rocks, coefficients of thermal conductivity from 2.92 to 5.67 μcal/cm·sec·°C were obtained. The results of the determinations by interval are given in Table 11 and Figure 23. Average thermal flow for the Kaspiysk field is 1.05 $\mu cal/cm^2 \cdot sec$.

Karaman. Tectonically this region is confined to the axial, most depressed part of the Tersko-Sulaksk depression. Two wells were studied here, Karaman-1 and the Temirgoe-research well. The wells are located 6 km apart. Rocks from the recent to the Chokraksk, inclusive, are involved in the structure of the wells' profile. All strata opened up by the drilling (108-4,007 m) were investigated.

The recent deposits of 43 m thickness are clays and argillaceous sands. /85
Beneath them to a depth of 342 m are Paleocaspian deposits of alternating clays, sands, or crumbled sandstones. Underlying them are Apsheron deposits of gray clays with a considerable content of aleurolitic material (fine grained sandstones and coarse grained aleurolites). At a depth of 1,260 m, Akchagyl deposits of clays, basically, (from pure to aleuritic) are encountered. From a depth of 1,935 m they are replaced by calcareous-aleurolitic clays of the Meotic deposits. Lower, in the 2,599-3,736 m interval, lie Sarmatian deposits, represented in the upper portion by a homogeneous layer of carbonaceous gray clays with varying content of aleuritic material. The clays of the Sarmatian deposits are distinguished from those lying higher by the presence in them of interstratifications of thinly imbricate, slightly yellowish hydromica. From 2,817 m the clays become arenaceous, micaceous, and

carbonaceous. At depths of 3,700 m hard, bedded, quartzitic, and feldspatic sandstones are encountered. In the 3,736-4,021 m interval Karagansk deposits represented from top to bottom by quartzitic sandstones, very hard marls, and clays were revealed. At 4,021 m were the Chokraksk deposits consisting basically of sandstones and aleurolites.

Despite the fact that there existed thermograms made after sufficient stabilization (more than 3 months), temperature gradients were evaluated by the "dual thermogram" method. Their values vary from 0.023 to 0.04 °C/m in the layer investigated.

Calculating with the corrections for moisture (up to 30% for the aquiferous sandstones), temperature and pressure, the coefficients of thermal conductivity were computed from the experimental data. They vary within broad limits -- from 1.54 mcal/cm·sec·°C for the Paleocaspian gray clays to 6.72 mcal/cm·sec·°C for the Sarmatian sandstones. Results of the determinations by intervals are given in Table 11 and Figure 24.

Average values for the thermal flow were determined for each of the stratigraphic complexes comprising the profile studied. In the calcareous clays of the Pleistocene (108-444 m interval studied) the thermal flow proved to be 0.58 μcal/cm^2·sec, in the rocks of the Apsheron (469-1,051 m) it was /86
0.73, and 0.99 for both the Akchagyl (1,500 m) and the Meotic (1,693-2,525 m). In the Sarmatian arenaceous clays (2,599-3,737 m) it was 1.20 μcal/cm^2·sec. Two determinations of the thermal flow were made in the sandstones of the Karagansk horizon (3,701-4,008 m) and the average of them was 1.76 μcal/cm^2·sec.

The low value for the thermal flow in the 108-444 m interval is evidently related to the effect of circulating underground water, which is also indicated by the considerable spread of the individual determinations. The cause of the abrupt increase of the thermal flow in the Karagansk sandstones is not completely understood. It is only possible to point out that these deposits, which contain thermal waters, are one of the thickest aquiferous horizons in that region.

The weighted average for the thermal flow in the 4 km thick layer of the /87
Karaman field according to depth was 0.96 μcal/cm^2·sec.

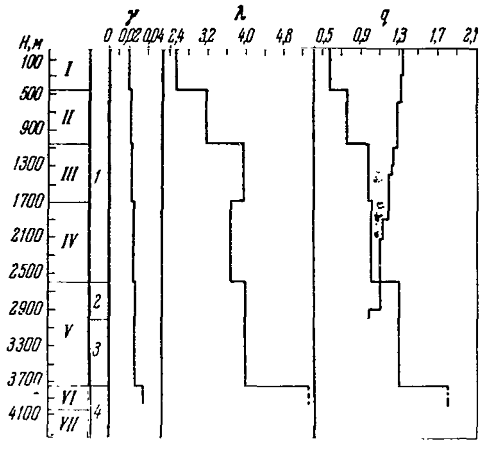

Figure 24. Changes in the temperature gradient (γ), thermal conductivity (λ), and thermal flow (q) in relation to depth in the Karaman area.

I, Paleocaspian; II, Apsheron; III, Akchagyl; IV, Meotic; V, Sarmatian; VI, Karazansk; VII, Chokraksk.

1, alternating clays and sandstones; 2, calcareous clays; 3, arenaceous clays with interstratification of sandstones; 4, sandstones, aleurolites.

Babayurt. Like the Sulak uplift described below, this structure underwent relative uplift during the Upper Quartenary, and it is one of the elements of the Sulak anticlinal zone, stretching in a latitudinal direction, which comprises the structure of the Tersko-Sulak depression. The interval investigated was 500-600 m, which is composed of Sarmatian yellow clays with interstratifications of sand. The coefficient of thermal conductivity for this interval, corrected for moisture, is 3.68 mcal/cm·sec·°C. The stable temperature gradient was evaluated by thermograms taken for this area and is 0.019 °C/m.

The average thermal flow in this region is 0.70 μcal/cm^2·sec. This value is close to that established in the same deposits in the Karaman area (0.760 μcal/cm^2·sec).

Sulak. Well No. 25 with a depth of 1,220 m revealed a layer of arenaceous clays with interstratifications of sand and coquina, stratigraphically related to the deposits of the Apsheron, Akchagyl, and Meotic stages. The 300-1,215 m interval was studied. The thermal conductivity of the rocks, corrected for moisture, varies from 1.56 to 4.59 μcal/cm·sec·°C. Because of the absence of thermometric observations here, the values of the stable temperature gradients were assumed to be analogous to those established for the Karaman field, which is not far away and has similar geologic-hydrological conditions. They are 0.024-0.027 °C/m.

Results of the calculation of thermal flows by interval in the region of the Sulak uplift are given in Table 11. The average thermal flow here is 0.65 μcal/cm^2•sec.

The following five regions investigated, in contrast to the foregoing, belong to the Skif platform (Kumac area arch zone).

Russkiy Khutor. This uplift consists of three shallower bosses (central, northern, and southern) and is represented by a typical platform structure of the brachyanticlinal type with very sloping dip of the limbs (the northwestern limb of the fold dips at an angle of 1°, the southeastern at 1°50').

Investigations were conducted in several wells lying near each other -- Nos. 4, 11, 13. The interval investigated (2,435-3,395 m) is composed of /88
Cretaceous and Jurassic limestones, sandstones, and aleurolites.

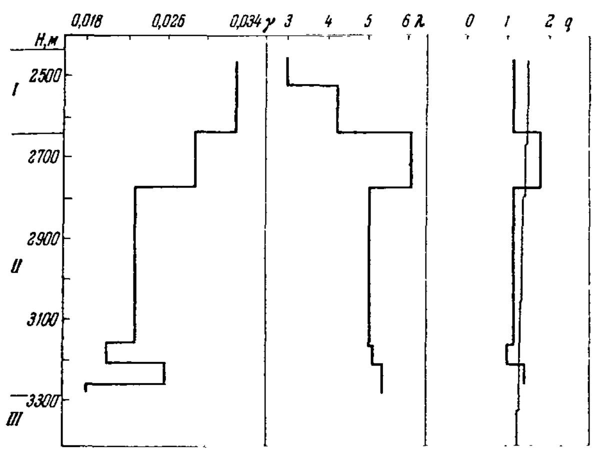

Figure 25. Changes in the temperature gradient (γ), thermal conductivity (λ), and thermal flow (q) in relation to depth in the Russkiy Khutor field.

I, Upper Cretaceous; II, Lower Cretaceous; III, Lower Jurrasic.

The stable gradients are according to existing spot measurements of temperature. The average value for the whole layer is 0.026 °C/m. With corrections for pressure and temperature (corrections for moisture were small, about 5%) the average thermal conductivity was 5.08 mcal/cm•sec•°C. Calculating according to these data the thermal flow is 1.32 μcal/cm^2•sec. In Table 11 and Figure 25 are given the results of the determination of the inductive thermal flow by intervals for this field. The temperature gradient values vary from 0.018 to 0.033 °C/m, and the thermal flow from 0.962 to 1.76 μcal/cm^2·sec.

Yuzhno-Sukokomskaya. This uplift is located 8 km southeast of Russkiy Khutor and consists of two bosses: a southwestern and a northeastern, separated by a depression of 55-60 m depth relative to the arches (along the roof of the Upper Jurassic deposits). The long axis of the fold extends N.E. 65°. Characteristic of the bosses of the fold is a slight asymmetry /89 with respect to the steepness of the southern limb in comparison with the northern. Along the roof of the Lower Cretaceous the structure of the Yuzhno-Sukhokumskaya uplift becomes less well defined. The structure is not defined, generally, in the deposits above the Maykopian.

Here wells No. 8, 11, 4 were studied. At a depth of 3,770 (bottom) they all revealed argillaceous sandstones of the Lower Jurassic. The investigated interval (1,900-3,730 m) is composed of clays of the Maykopian series in the upper portion, and, in the lower, of sandstones, aleurolites, and limestones of the Cretaceous and Jurassic systems. The stable gradients were evaluated according to numerous spot measurements of temperatures in the wells and thermograms taken after an 11 month period of idleness. For the interval 1,900-2,300 m the average temperature gradient is 0.035 °C/m, and for the 2,500-3,700 m interval it is 0.023 °C/m. With corrections for pressure and temperature the coefficient of thermal conductivity for the same intervals is, respectively, 3.78 and 5.46 mcal/cm·sec·°C. Results of the determinations by interval are given in Figure 26 and in Table 11.

The weighted average values of the thermal flow for the two wells located in the center of the boss (8 and 11), and for well No. 4, located on the limb, are 1.17 and 1.37 μcal/cm^2·sec, respectively.

The Solonchakovaya uplift is an asymmetrical brachyanticline of sublatitudinal strike with a relatively steep northern and a sloping southern limb. Eastward from the dome the fold is severely constricted, forming a structural promontory.

Wells 2 and 3 of the field were studied in geothermic relationship. The interval investigated (2,900-3,552 m) is represented by dolomites and limestones, argillites and aleurolites of the Lower Cretaceous and Upper Cretaceous. The stable gradients were evaluated from spot measurements of temperature for the area, and they vary, for the part of the profile studied, from 0.017 to 0.025 °C/m. With corrections for pressure and temperature the coefficients of thermal conductivity vary from 3.40 to 6.56 mcal/cm·sec·°C. The results of the determinations by interval are given in Table 11 and Figure 27.

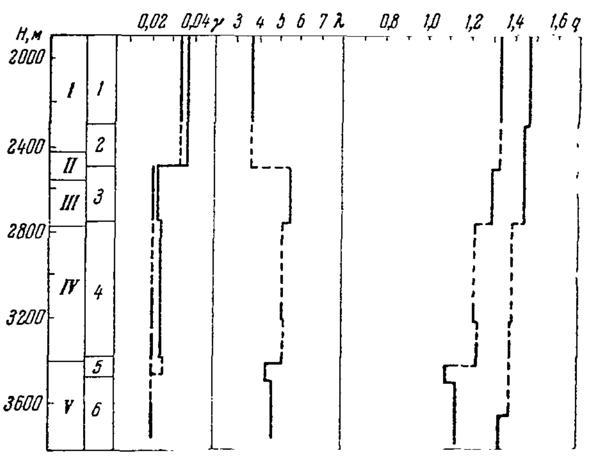

Figure 26. Changes in the temperature gradient (γ), thermal conductivity (λ), and thermal flow (q) in relation to depth in the Yuzhno-Sukhkumskaya field.

I, Maykopian; II, Foraminiferous horizon; III, Upper Cretaceous; IV, Lower Cretaceous; V, Jurassic. 1, argillaceous-member; 2, argillaceous-aleurolitic member; 3, limestone with interstratification of clay; 4, argillaceous-arenaceous member; 5, argillaceous-carbanaceous member; 6, aleurolitic-argillaceous-arenaceous member.

The average thermal conductivity for the Mesozoic deposits in the 3,422-3,735 m interval is 5.88 mcal/cm·sec·°C, and the average temperature gradient for the same interval is 0.0175 °C/m. Average thermal flow for the Mesozoic deposits is 1.03 μcal/cm^2·sec. /91

Stepnaya. This brachyanticline is located northeast of the Solonchakovaya uplift. The well studied here was No. 1. The investigated interval (2,829-2,935 m) is comprised of sandy-aleurolitic rocks and limestones of the Cretaceous. The temperature gradient, evaluated from a thermogram and also using spot measurements, is 0.025 °C/m. The average coefficient of thermal conductivity, corrected for pressure and temperature, was determined as 5.26 mcal/cm·sec·°C. The average thermal flow for the Stepnaya field is 1.32 μcal/cm^2·sec.

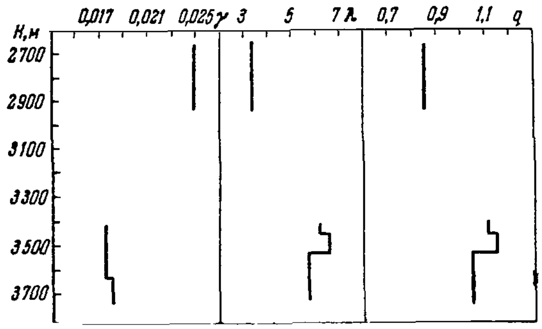

Figure 27. Changes in the temperature gradient (γ), thermal conductivity (λ), and thermal flow (q) in relation to depth in the Solonchakova Field.

Bazhigan. The structure is located on the sourthern submerged portion of the Kuma area arch. Two wells were examined (No. 2 and 3). The interval investigated (3,900-4,000 m) is composed of aleurolites and sandstones belonging to the rocks of the folded bedrock. Average thermal conductivity is 4.04 mcal/cm·sec·°C. Temperature gradients were evaluated from spot measurements; the average /92
value for both wells is 0.039 °C/m.

The average thermal flow in the Bazhigan field at the interval studied is 1.58 μcal/cm^2·sec.

The investigations carried out permit characterization of the thermal flow in various elements of the tectonic structure of the region studied (Table 12, Figure 28).

Seven of the regions investigated are located within the boundaries of the Cenozoic Tersk-Kaspiysk forward depression. Four of them -- Izberbash, Makhachkala, Kaspiysk, Gasha -- belong to the Kulsary-Divichinsk depression (Gasha to the western anticlinal zone within its borders, the others to the eastern), and three -- Karaman, Sulak, Babayurt -- belong to the Tersk-Sulak depression. In these regions, with the exception of the Kaspiysk area, the average value of the thermal flow varies from 0.65 to 0.96 μcal/cm^2·sec. With an average thermal flow value of 1.05 μcal/cm^2·sec according to depth in the Kaspiysk field, sharp increases in the value (1.4-2.1 μcal/cm^2·sec) were determined in the Karagan-Chokraksk aquiferous sandstones, which is /93
evidently related to the unusual geothermic conditions in these horizons. The conductive thermal flow in the Tersk-Kaspiysk depression is 0.85 μcal/cm^2·sec, averaged by the field. This agrees well with the worldwide data concerning low thermal flow in forward depressions and internal basins in regions of

Cenozoic tectonic activity (cf. Table 6). The causes of such lowering of the thermal flow need further study. It is assumed that the basic ones among them are the variability of the geothermal field in zones of intense vertical movement of the Earth's crust, the energy-consuming processes in the depths of such zones, and several other depth-related factors. In our opinion it is also possible that the reduction of the thermal flow in this structural region is related to the effect of the hydrodynamic factor, in which case the established value can characterize only the conductive constituent, and not the total rate of deep heat loss.

TABLE 12. RESULTS OF THE DETERMINATION OF THERMAL FLOW IN THE DAGESTAN TERRITORY

Field studied	Depth interval studied, in m	Avg. thermal flow in $\mu cal/cm^2 \cdot sec$	No. of determinations
Cenozoic Tersk-Kaspiysk depression			
Izberbash	10-1,962	0.74	19
Kaspiysk	1,420-1,865	1.05	10
Makhachkala	1,434-1,683	0.96	3
Gasha	2,130-3,146	0.87	5
Karaman	108-4,008	0.96	26
Babayurt	500-600	0.70	2
Sulak	308-1,215	0.65	7
Avg. for depression		0.85	
Post-Hercynian Skif platform			
Russkiy Khutor	2,435-3,395	1.21	9
Yuzhno-Sukhokumskaya	1,900-3,730	1.25	9
Solonchakovaya	3,422-3,622	1.03	14
Stepnaya	2,600-2,950	1.32	2
Bazhigan	3,852-4,000	1.58	2
Avg. for platform		1.30	

The other five fields we investigated -- Russkiy Khutor, Yuzhno-Sukhokumskaya, Solanchakovaya, Stepnaya, and Bazhigan -- are located within the Post Hercynian Skif platform and belong to the Kuma area uplifts comprising the Tersk-Kumsk basin. The average thermal flow, according to depth, in these regions fluctuates from 1.03 to 1.58 $\mu cal/cm^2 \cdot sec$. The average for the whole area of the platform is 1.30 $\mu cal/cm^2 \cdot sec$ according to these data, which agrees well with the established analysis of world-wide data on thermal flow in the regions of Hercynian folding (see Table 6).

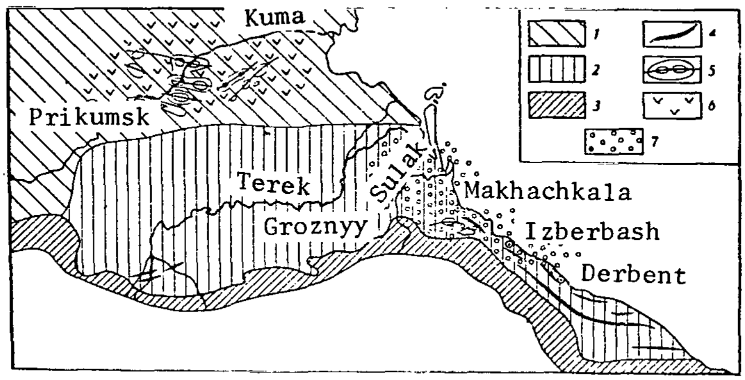

Figure 28. Thermal flow distribution in Dagestan

1, Post Hercynian Skif platform; 2, Tersk-Kaspiysk marginal depression; 3, miogeosynclinal zone of the Greater Caucasus; 4, strikes of the axes of the anticlinal zones of the Dagestan Piedmont; 5, Kuma area uplift zone; 6, thermal flow zone with predominant values greater than 1.0 $\mu cal/cm^2 \cdot sec$; 7, thermal flow zone with values primarily below 1.0 $mcal/cm^2 \cdot sec$.

Thus the geothermal investigations produce essentially different values for the thermal flow in tectonically different elements of the area studied. The variation of the individual thermal flow values established in a number of cases may be produced by circumstances of a different nature. Such irregular deviations of the thermal flow from the average value is probably caused by chance factors, generally. The tendency of the thermal flow to change with depth, observed in the individual cases, may be related to exothermic processes in the sedimentary layer (particularly the increase in the flow from the bottom upward in the Izberbash and Gasha fields), then the increase of the thermal flow with depth, as established for the Karaman field, is probably related to the absorption of heat.

CHAPTER VI

/94

EVALUATION OF THE EMISSION OF RADIOGENIC HEAT IN THE SEDIMENTARY LAYER OF DAGESTAN

The establishment of exhaustive regional geothermal data requires, together with experimental determination of the magnitude of the thermal flow actually observed in the Earth's crust (by means of thermometric observations and investigations of thermal conductivity), analysis of the role of various sources of deep heat -- their magnitude, distribution in the vertical profiles and according to field, and such similar factors. Of primary interest in this respect is the effect of the energy of radioactive decay, which, although recognized as the primary source of intra-Earth heat, still has not been characterized by direct evaluations according to regions. In this connection we attempted to evaluate the geothermal significance of the decay of radioactive elements dispersed in the sedimentary strata of the area studied.

Based on the hypothesis of R. Strutt, J. Jola, and G. Jeffries, that the radioactive elements are concentrated in one layer H of the Earth's surface, A. N. Tikhonov determined temperatures for a steady-state thermal field

$$U_0(X) = \frac{A}{\lambda}\left(H_X - \frac{X^2}{2}\right) \quad \text{when } 0 \leq X \leq H,$$

$$U_0(X) = \frac{AH^2}{2} \quad \text{when } H \leq X < \infty$$

where $U_0(X)$ is the temperature at depth X; A is the density of the thermal source; and λ is the thermal conductivity.

The thermal flow at the surface of the Earth is determined by the formula /95

$$q_0 = \lambda \frac{dU_0(0)}{dx} = AH,$$

while the full value of the thermal flow is obtained only when H is the thickness of a layer such that all the radioactive elements creating the thermal flow are concentrated within it. Determination of the radioactive element content in lithographically homogeneous layers for each interval, and the subsequent calculation of the amount of heat generated in their decay, makes possible determination of the radioactive component of the thermal flow in that interval from the relationship $\Delta q = AH$, where A is the thermal energy of the radioactive sources in the layer of thickness H.

Calculating the amount of heat generated in the form of radioactive decay in each interval, it is possible to obtain the total amount of the thermal flow in an ideal situation, i.e., in the absence of lateral heat losses, energy-consuming processes taking place with an absorption of heat, and heat removal by underground water. But such a method of calculation holds true only if there is but one heat source acting in the layer under study, namely radioactive decay, and if the content of radioactive elements in the rocks is constant.

A complete solution to the problem of the role of radiogenic heat in the Earth's thermal regimen is seriously hampered by the lack of sufficient information about the distribution of radioactive elements within the body of the planet. "Little is known to us concerning the changes in the radioactive element content with depth, and this is the decisive obstacle to the further development of thermal theory. The differences between the maximum and minimum contents of radioactive elements and the probable differences in their distributions is such that it can lead to considerable different results," (Birch, 1954). Considering that our investigations were concerned with the sedimentary layer of Dagestan, we shall dwell briefly on general information about the radioactivity of the sedimentary rocks.

General Information Concerning the Radioactivity of Sedimentary Rocks /96

The radioactivity of sedimentary rocks is related to the presence of potassic, especially of uranium and thorium, uranium and thorium-containing minerals in them, and also of absorbed radioactive elements. The weighted average content of radioactive elements in the whole sedimentary layer is nearly the same as their content in acidic igneous rocks.

Almost all sedimentary rocks contain uranium in amounts on the order of 10^{-6} g/g (and some, especially black marine clay shales and phosphates, up to 10^{-4} g/g) and several times as much thorium. On the other hand, rocks such as sandstones and limestones may be so poor in uranium that its content sometimes approaches the limits of accurate determination. The radioactivity differs for different lithologic types of rock.

Clays and clay shales. Among the sedimentary rocks (excluding potassium salts) the clays have, on the average, the highest radioactivity. The radioactive element content in deep sea clay deposits reaches $57 \cdot 10^{-12}$ g-equiv. Ra/g and more. Continental and shallow water sediments are less radioactive (from $3 \cdot 10^{-12}$ to $30 \cdot 10^{-12}$ g-equiv. Ra/g). The most radioactive of the shales are the black marine sapropelic varieties.

The relatively high radioactivity of the clays and clay shales is explained by the following factors: a high sorption of uranium, radium, thorium, and potassium in the clay particles; the presence of potassium, thorium, and hexavalent uranium minerals; the formation of tetravalent uranium minerals in a reducing medium; and the formation of solid solutions (some of the radioactive minerals can form solid solutions with clay minerals). The relatively high radioactivity of the clays and argillaceous rocks is also explained by the relatively high potassium content of these rocks (up to 6.5%).

Sandstones. Most often the radioactive elements contained in sandstones are in the form of isomorphic impurities in the minerals of the heavy fraction, for which a significantly large Th to K ratio and a small K content are characteristic. Radioactive elements may also occur in the clayey cement of these rocks in adsorbed form. Ordinarily sandstones contain /97
only traces of radium, uranium, and thorium, and a little potassium. A minimum content of radioactive elements is characteristic of the well-sorted marine, basically quartzitic, sandstones.

A high content of radioactive elements, depending on the shaliness, has been established for the argillaceous varieties of sandstone, and also for sandstones with organic impurities. The nature of the increase in radioactivity in relation to the shaliness of the sandstone is shown in Figure 29 (Kobranova, 1962).

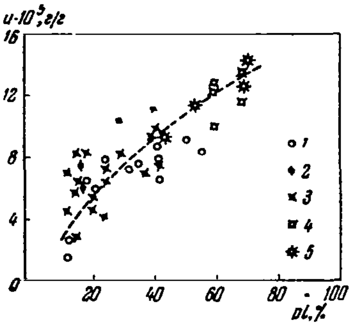

Figure 29. Dependence of uranium content on shaliness for sandy-argillaceous rocks (V. N. Kobranova)

1, sand; 2, sandstone; 3, clayey sand and koalinized sandstone; 4, clay; 5, sandy clay.

Carbonates. Pure marine limestones and dolomites are only slightly radioactive, as a rule. Their uranium content does not exceed $4 \cdot 10^{-6}$ g/g. The weak radioactivity of the organic limestones is caused by the oxidizing conditions under which these deposits are formed. Shaliness increases the radioactivity of the carbonaceous rocks. In some profiles of petroleum deposits, dolomitized limestones of abnormally high radioactivity have been found. Considerable, even commercial radioactivity is found in vanadium-rich marine limestones.

The radioactivity of the marls is, on the average, higher than that of the pure limestones and, in a number of cases, is close to that of the clays. A smaller amount of radioactivity is characteristic for the light colored marls, and a greater amount of radioactivity for the dark colored.

The characteristics of the radioactivity of different types of sedimentary rocks, combined from the data of N. S. Boganik (1966) and V. N. Kobranova (1962), are given in Table 13.

On the whole, the sedimentary rocks can be combined into three groups /99
according to their degree of radioactivity:

1. Rocks with low radioactivity, which include well-sorted and weakly cemented monomineral quartzitic sands, sandstones, aleurolites, pure limestones, and dolomites.

2. Rocks with moderate radioactivity -- clayey varieties of sedimentary rocks (argillaceous sands, sandstones, aleurolites, argillaceous limestones and dolomites, and some marls), as well as rocks with organic impurities.

3. Rocks with high radioactivity -- potassium salts, monazitic and orthitic sands, deep sea clays, and globigerina ooze.

TABLE 13. CONTENT OF RADIOACTIVE ELEMENTS IN SEDIMENTARY ROCKS

Lithologic composition	$U \cdot 10^{-6}$				$Th \cdot 10^{-6}$				K			K	Ra 10^{-12}
	N.S. Boganik (1966)			Kobranova (1962)	N.S.Boganik (1966)			Kobranova (1962)	N.S. Boganik (1966)			V.N.Kobranova (1962)	
	min.	max.	av.		min.	max.	av.		min.	max.	av.		
Clays and clay shales	1.2	5.0	4.0	4.3	10	15	11	13	0.027	0.065	0.032	--	1.3
Sandstones	1.2	4.5	3.0	up to 4.0	6	15	10	--	0.011	0.013	0.012	--	0-1.5
Limestones	1.3	1.1	1.4	1.5	1.1	1.4	1.8	0.5	0.026	0.083	0.003	--	0.5
Dolomites	--	--	--	0.3	--	--	--	--	--	--	--	0.26	0.11

/98

Methods for Determining Uranium, Thorium, and Potassium Concentrations in Rocks

The process of radioactive decay represents an example of the transformation of mass into energy in conformity with Einstein's equation $\Delta E = \Delta mc^2$. This energy is manifested in the form of the kinetic energy of alpha and beta particles, parent nuclear recoil, and in the radiation of quantum x-rays, γ-rays, and neutrinos.

There are two ways, in principle, of determining the energy of radioactive decay: the first is to determine the energy of all the individual particles and quanta; the second is to determine by mass-spectrometry the differences in the masses of the parent and the end products. Practically, the differences of mass in the radioactive nuclei are best determined by a summation of the individual radiations. If it were possible to disregard the effect of neutrino emission, the amount of heat emitted would be simply the heat energy equivalent of the mass difference between the parent and the daughter products; but since the neutrino removes part of the energy and is not absorbed by the Earth, then appropriate corrections are introduced.

Radiometric methods based on measuring the radioactive radiation of the test specimens are commonly used to determine the radioactive element content of rocks. The radioactivity of rocks according to their γ-radiation is expressed in percentages of uranium content, while the counting rate of /100
the γ-quanta from the rock sample is compared with the counting rate of γ-quanta from a standard specimen with a given uranium content. Determination of the uranium, thorium, and potassium contents of the rock samples with low contents of radioactive elements was carried out on an LSU-5K unit using an NaJ(Tl) as the phosphor pickup.

In irradiation of the phosphor with γ-rays, part of the total number of γ-quanta falling on the phosphor forms charged particles, but the remainder pass through the phosphor without loss of energy. The formation of secondary electrons during the passage of the γ-quanta through the phosphor takes place as a result of photoelectric absorption, Compton scattering, and pair formation.

In determining the total activity of the sample, when it is necessary to record the greatest possible number of γ-quanta falling on the phosphor regardless for energy, impulses emanating from any event of the reaction are recorded. In this case the number recorded quanta may be calculated by the formula

$$N = \Sigma N_0^i (1 - e^{\mu_i d}),$$

where N_0^i is the number of γ-quanta falling on the phosphor; N is the number of γ-quanta forming secondary electrons in the phosphor; μ_i is the linear coefficient of the γ-quanta interaction of the given energy in the phosphor.

The coefficient μ_i represents the sum of the individual interaction factors of the three current processes: photoelectric absorption, Compton scattering, and pair formation. The effectiveness of γ-radiation recording by a scintillation counter with an NaI(Tl) phosphor depends on the energy of the γ-quanta and the thickness of the phosphor. With a thickness of 1.5 cm it is practically 100% for energies of 0.1 Mev and rapidly decreases with an increase in energy of the discernible γ-quanta; with energies of 2.6 Mev it is approximately 18%. For a very thick phosphor, the increase in the effective- /101 ness with an increase the γ-quanta energies occurs more slowly. Thus, a scintillation counter equipped with a 5-cm NaI(Tl) crystal will provide a recording efficiency of the order of 50% for γ-quanta energies of 2.6 Mev. Since the natural radiation energy of γ-quanta varies within broad limits, best recording is provided by a phosphor of rather large dimensions. The apparatus we used was equipped with NaI(Tl) crystals of 40 mm in diameter and a height of 50 mm.

With the LSU-5K it is not only possible to record γ-quanta but also to measure their energy. Integral and differential methods exist for the investigation and graphic representation of the pulse distribution amplitudes. The integral method is based on the sequential recording of the pulse count at different levels of pulse amplitude discrimination.

For the solution of this problem in a general case, it is necessary to measure four parameters of radioactive radiation from the sample and in the case of each of these measurements maximum sensitivity to the component being measured and minimum sensitivity to the other components must be secured.

Ideal conditions of measurement, when each of the measurements would characterize the content of only one of the components measured, were not achieved; the higher the coefficient of separation, the more accurate is the analysis, i.e., the higher the sensitivity to the given component in the appropriate channel.

Investigations in recent years have shown that the greatest sensitivity with high coefficients of separation, in the determination of radium and thorium, can be assured in differential measurements of the γ-radiation in the energy range of 240 kev and 350 kev with the help of a scintillation spectrometer.

For the determination of uranium it is possible to use measurements of either β-radiation or γ-radiation in the γ-quanta energy range of approximately 100 kev. From Table 14 it can be seen that if the emission ratio of uranium, radium, and thorium are approximately equal, for potassium the contribution of its radiation with β-measurements is of a higher order than with γ-measurement in the 90-105 kev range. Therefore, in determining uranium by the β-radiation, errors in the potassium determination will affect more in the accuracy of the uranium determination. For this reason γ-measurement is chosen with an energy range of 90-105 kev for determining uranium, which assures a high degree of accuracy of the analysis. For determining and excluding the effect of potassium interference, either differential γ-measurements in the 1.4-1.5 Mev range /102
(photopeak K_{40} - 1.5 Mev) or β-measurements may be used.

TABLE 14. EMISSION RATES OF RADIOACTIVE COMPONENTS IN MEASUREMENTS OF β-RAYS AND γ-RADIATION IN THE 90-105 kev RANGE.

Indicator	U	Ra	Th	K
β-rays	0.288	0.712	0.392	$0.762 \cdot 10^{-4}$
γ-radiation	0.480	0.520	0.191	$6.550 \cdot 10^{-4}$

On the basis of the measurements of the samples investigated in four channels it is possible to set up the following equations:

$$A_1 = A_U^1 \cdot U + A_{Ra}^1 \cdot Ra + A_{Th}^1 \cdot Th + A_K^1 \cdot K,$$
$$A_2 = A_U^2 \cdot U + A_{Ra}^2 \cdot Ra + A_{Th}^2 \cdot Th + A_K^2 \cdot K,$$
$$A_3 = A_U^3 \cdot U + A_{Ra}^3 \cdot Ra + A_{Th}^3 \cdot Th + A_K^3 \cdot K,$$
$$A_4 = A_U^4 \cdot U + A_{Ra}^4 \cdot Ra + A_{Th}^4 \cdot Th + A_K^4 \cdot K,$$

where A_1, A_2, A_3, A_4 are the activities of the test sample for each measurement in the corresponding channels, expressed in the equivalent of a stable amount of uranium; $A_a^{(i)}$, $A_{Ra}^{(i)}$, $A_{Th}^{(i)}$, $A_k^{(i)}$ are the uranium equivalents of the uranium group, radium group, thorium, and potassium according to measurements of the radiation energy of amounts of U_3O_8 energetically equivalent to the amount of uranium, radium, thorium, and potassium in the corresponding channels; U, Th, Ra, K are the contents of uranium, thorium, radium, and potassium in percentages of their uranium equivalents. Solution of these equations is according to the following formulas:

$$U = a_1A_1 + b_1A_2 + c_1A_3 + d_1A_4,$$
$$Ra = a_2A_1 + b_2A_2 + c_2A_3 + d_2A_4,$$
$$Th = a_3A_1 + b_3A_2 + c_3A_3 + d_3A_4,$$
$$K = a_4A_1 + b_4A_2 + c_4A_3 + d_4A_4,$$

where $a_1 - a_4$, $b_1 - b_4$, $c_1 - c_4$, $d_1 - d_4$ are the coefficients obtained by solution of all four equations.

Determination of the coefficients $A_U^{\prime}$, $A_{Ra}^{\prime}$, $A_{Th}^{\prime}$, $A_K^{\prime}$ is carried out from the results of γ-measurements of standard samples of equivalent uranium, uranous-uranic oxides, thorium, and potassium in each of the selected channels according to the following formulas: /103

$$A_U^i = \frac{N_U^i \cdot Q_{UR} \cdot P_{UR}}{N_{UR}^i \cdot Q_U \cdot P_U}, \quad A_{Ra}^i = \alpha - A_U^i,$$
$$A_{Th}^i = \frac{N_{Th}^i \cdot Q_{UR} \cdot P_{UR}}{N_{UR}^i \cdot Q_{Th} \cdot P_{Th}}, \quad A_K^i = \frac{N_K^i \cdot Q_{UR} \cdot P_{UR}}{N_{UR}^i \cdot Q_K \cdot P_K},$$

where N_U^i, N_{UR}^i, N_{Th}^i, N_K^i are the pulse counting rates after deduction of the background in measurements of standard amounts of uranic-uranous oxides, equivalent uranium, thorium, and potassium in the corresponding channels; Q_U, Q_{UR}, Q_{Th}, Q_K are the contents of uranium, equivalent uranium, thorium, and potassium in the standard samples, in %; P_U, P_{UR}, P_{Th}, P_K are the weights of the corresponding standard samples, in grams.

In the determination of A_U^5, A_{Ra}^5, A_{Th}^5, A_K^5, no corrections for weight are introduced since the β-measurements are made in a saturated layer.

Then

$$A_U^5 = \frac{N_U^5 \cdot Q_{UR}}{N_{UR}^5 \cdot Q_U}, \quad A_{Ra}^5 = \alpha - A_U^5,$$

$$A_{Th}^5 = \frac{N_{Th}^5 \cdot Q_{UR}}{N_{UR}^5 \cdot Q_{Th}}, \quad A_K^5 = \frac{N_K^5 \cdot Q_{UR}}{N_{UR} \cdot Q_K},$$

and the working formulas take on the form:

$$U = \frac{a_1}{F} A_1 + \frac{a_2}{F} A_2 + \frac{a_3}{F} A_3 - \frac{a_4}{F} A_5,$$

$$Ra = \frac{b_1}{F} A_1 + \frac{b_2}{F} A_2 + \frac{b_3}{F} A_3 + \frac{b_4}{F} A_4,$$

$$Th = \frac{c_1}{F} A_1 + \frac{c_2}{F} A_2 + \frac{c_3}{F} A_3 + \frac{c_4}{F} A_5,$$

$$K = -\frac{d_1}{F} A_1 - \frac{d_2}{F} A_2 - \frac{d_3}{F} A_3 + \frac{d_4}{F} A_5,$$

where U, Th, Ra, K are the contents of the elements, in %; A_1, A_2, A_3, A_5 are the sample activities (in %) of equivalent uranium in the corresponding channels; a_i, b_i, c_i, d_i are the coefficients obtained in the solution of the system of equations.

As concerns the accuracy of the method of measurement employed, the following should be kept in mind:

1. The sensitivity threshold of the analysis for uranium, with a radium /104
and thorium content of $n \cdot 10^{-4}$ and several percents of potassium, is approximately $2\text{-}3 \cdot 10^{-4}$%. Increase of the radium and thorium contents lowers the accuracy of uranium determination, the effect of the potassium is small.

2. Sensitivity threshold of the thorium determination with $n \cdot 10^{-4}$% uranium and radium content and several percents of potassium is $1.5 \cdot 10^{-4}$%. The presence of radium affects the accuracy of the determination but uranium and potassium have no effect.

3. Sensitivity threshold of the analysis for potassium with a radioactive component of $n \cdot 10^{-4}$% is 0.35%. The presence of uranium and thorium has little effect on the accuracy of the potassium determination, radium has a somewhat greater effect.

Distribution of Radioactive Elements in the Sedimentary Rock Cover and the Thermal Effect of Their Decay

Determination of the concentration of radioactive elements in the rocks comprising the thermometrically and thermophysically studied intervals of the profiles in the investigated regions of Dagestan, and of the thermal effect of their decay (Table 15) revealed the peculiarities of their distribution (Table 16) and permitted quantitative evaluation of the thermal capacity of radioactive decay, both in the individual lithologo-stratigraphic members (Table 17) as well as within the boundaries of that entire portion of the sedimentary cover studied (Table 18).

It was established that the radioactive element content is directly related to the lithologic composition of the rocks (Table 17). The clays have the highest radioactivity of all the sedimentary rocks of Dagestan, and the limestones have the lowest, although it varies in the latter within broad limits. No relationship was observed between the radioactive content of the rocks and their age or the depth of the strata. Neither has any clear regularity been discovered yet in the distribution of the radioactive elements in the different parts of the territory studied. At the same time, the high radioactivity of the Mesozoic rocks of the Skif platform cover, in comparison with the formations of the same age in the Tersk-Kaspiysk depression, attracts the attention -- for a 100 m thick layer in the Russkiy Khutor field the thermal effect of radioactive decay is 0.0060 μcal/ /112
$cm^2 \cdot sec$, as shown in Table 18, while in the Gasha field it is only 0.0035 $\mu cal/cm^2 \cdot sec$.

The results of our investigations agree well with the data in the literature. For example, in the Karaman well, which was the most studied one from the radiogeochemical point of view, the average thermal effect of the decay of radioactive elements dispersed in the 100-3,000 m interval was $1.16 \cdot 10^{-12}$ cal/cm sec, which is very close to the $1.3 \cdot 10^{-12}$ used by A. N. Tikhonov in his calculations (Tikhonov, Samarskiy, 1953).

TABLE 15. RESULTS OF THE INVESTIGATION OF RADIOACTIVE ROCKS AND THE EMISSION OF RADIOGENIC HEAT IN THE STUDIED REGIONS OF DAGESTAN

Lithologic composition	Age	Depth of test samp in meters	Content, %			Heat emission, 10^{-12} cal/cm^3·sec		
			$U \cdot 10^{-4}$	$Th \cdot 10^{-4}$	K	U	Th	K
				Yuzhno-Sukhokumskaya				
Clays	Pg	1999—2007	6,4	0,3	1,793	0,373	0,005	0,037
	Cr_2	2439—2444	46,5	7	1,128	2,545	0,110	0,039
	»	2545—2550	26,4	8,5	1,049	1,445	0,134	0,020
	Cr_1	3352—3359	20	2	1,56	0,117	0,0335	0,032
	J_3	3412—3418	17	11	—	0,990	0,185	—
Sandstones	Cr_1	3140—3146	—	9	1,08	—	0,145	0,021
	»	3146—3150	1,2	7,3	1,244	0,067	0,117	0,021
	»	3150—3154	29,2	4,1	1,035	1,63	0,069	0,02
	»	3236—3292	35,5	4,5	1,917	1,063	0.075	
	»	3238—3293	32	2,3	—	1,788	0,0369	—
	»	3281—3283	19	7	1,56	1,19	0,117	0,032
	»	3302—3308	2	8	—	0,112	0,129	—
	»	3306—3312	15	5	0,67	0,84	0,0161	0,0132
	»	3308—3315	—	9	1,08	—	0,145	0,0090
	»	3312—3318	—	8	0,11	—	0,128	0,0020
	»	3339—3345	5	7	1,20	0,29	0,117	0,025
	J_3	3347—3350	25,4	6	—	1,479	0.100	—
	»	3352—3359	20	2	1,56	0,117	0,0335	0,032
Sandstones	»	3409—3411	29,5	6,4	—	1,72	0,107	—
	»	3412—3418	—	8	0,11	—	0,128	0,022
	»	3418—3425	5	8	3,35	0,29	0,134	0,069
	J_2	3701—3706	12,6	14	1,282	0,73	0,234	0,026
Dolomites	J_3	3435—3442	9	—	0,120	0,544	—	0,026
	»	3447—3455	2,6	7,9	1,20	0,66	0,112	0,024
Limestones	Cr_2	2759—2762	1,96	8,3	2,318	0,107	0,130	0,045
				Russkiy Khutor				
Clays	J_2	3311—3316	45	—	—	2,60	—	—
	J_1	3534—3538	29	—	18	1,625	0,3002	—
	Cr_1	3259—3265	13	9	—	0,751	0,149	—
Argillaceous aleurolites	»	3049—3054	13	12	—	0,754	0,200	—
	»	3186—3192	22	5	—	1,287	0,0841	—
	»	3192—3202	33	4	—	1,930	0,0673	—
	»	3185—3192	4	5	—	0,234	0,168	—
	»	3152—3157	17	6	—	0,994	0,2690	—
	»	3207—3213	28	4	—	1,672	0,0665	—
	»	3213—3219	27	—	—	1,56	—	—
	J_2	3390—3395	9	11	1,68	0,522	0,184	0,0343
Aleurolites	Cr_1	2646—2651	6	—	9	0,328	0,142	—
	»	2651—2656	8	—	—	0,438	—	—
	J_2	3390—3395	28	7	—	1,624	0,117	—

Note: Commas indicate decimal points.

TABLE 15. (Continued) /106

Lithologic composition	Age	Depth of test samp in meters	Content, %			Heat emission, 10^{-12} cal/cm^3·sec		
			$U \cdot 10^{-4}$	$Th \cdot 10^{-4}$	K	U	Th	K
Russkiy Khutor								
Sandstones	Cr_1	3044—3049	2	1	1,13	0,116	0,0167	0,023
	»	3147—3152	3	14	0,03	0,175	0,235	0,0006
	»	3271—3276	6	23	—	0,347	0,382	—
	J_2	3316—3321	2	—	—	0,116	—	—
Limestones	Cr_2	2452—2457	19	—	—	1,085	—	—
	»	2478—2484	32	—	—	1,823	—	—
	»	2479—2486	4	7	1,89	0,223	0,115	0,0379
	Cr_1	3251—3259	13	5	1,23	0,751	0,033	0,0250
	»	3288—3293	18	13	—	0,61	0,226	—
Dolomites	J_2	3305—3310	7	7	0,90	0,404	0,166	0,0313
Solonchakovaya								
Limestones	Cr_2	2908—2915	2	8	—	0,1105	0,129	—
	»	2915—2921	21	—	—	1,22	—	—
	»	2930—2935	2	19	—	0,114	0,312	—
	»	2930—2935	6	3	0,02	0,342	0,131	0,0004
	»	2935—2941	3	44	—	0,171	0,122	—
Argillites	Cr_1	3530—3535	—	12	1,13	—	0,20	0,0230
		3535—3540	8	2	0,34	0,464	0,034	0,0069
		3579—3584	37	1	—	1,146	0,0167	—
	J_2	3681—3686	36	—	—	2,089	—	—
Aleurolites	Cr_1	3434—3439	5	36	—	0,288	0,579	—
	»	3444—3448	3	15	—	0,173	0,249	—
Sandstones	J_3	3670—3676	—	7	—	—	0,115	—
	J_2	3691—3696	40	—	—	2,24	—	—
Bazhigan								
Sandstones	J_3	3510—3513	1	8	0,26	0,059	0,129	0,0051
	J_2	3760—3765	3	20	3,93	0,163	0,322	0,0783
Arenaceous Limestones	»	3602—3603	3	4	0,44	0,175	0,101	0,0009
Argillaceous limestones	»	3608—3613	2	6	1,99	0,1165	0,0993	0,0479
Stepnaya								
Clays	Cr_2	2642—2647	34	23	—	1,9	0,37	—
	»	2647—2652	31	9	—	1,755	0,145	—
	»	2665—2670	—	8	1,99	—	0,129	0,0033
	»	2943—2948	34	31	—	1,90	0,486	—
	Cr_1	3339—3341	37	39	—	2,067	0,628	—
Limestones	Cr_2	2893—2898	1	31	—	0,057	0,496	—
	»	2929—2935	2	8	2,44	0,118	0,132	0,049
Glauconitic Sandstone	Cr_1	3228—3233	34	25	—	1,90	0,402	—

Note: Commas indicate decimal points.

Lithologic composition	Age	Depth of test samp in m	Content, % U·10^{-4}	Th·10^{-4}	K	Heat emission, 10^{-12} cal/cm^3·sec U	Th	K
				Makhachkala				
clays	N_1krg + tsch	1659—1664	14	9	4,63	0,7830	0,1448	0,0910
Sands & sandstones	»	1503—1508	2	7	0,72	0,0935	0,0935	0,0124
	»	1513—1523	—	140	0,23	—	2,2600	0,0056
	»	1750—1755	3	15	0,40	0,1630	0,2470	0,0079
	»	1755—1760	4	8	1,64	0,2240	0,1237	0,0322
				Gasha				
Sandstones	Cr_1	3104—3109	1	19	2,95	0,0510	0,2800	0,0530
	»	3118—3124	—	13	2.24	—	0,1916	0,0404
	»	3154—3164	2	14	2,70	0,1025	0,2064	0,0487
	»	3199—3206	3	14	2,82	0,1540	0,2064	0,0509
Limestones	Cr_2	2126—2130	2	6	0,48	0,1104	0,0665	0,0009
	»	2778—2782	—	11	—	—	0,1770	—
	»	2815—2824	—	—	0,22	—	—	0,0094
	»	2876—2880	—	18	2,20	—	0,2380	0,0896
	»	2906—2912	2	14	2,94	0,2050	0,2251	0,0579
	»	2948—2954	—	14	1,77	—	0,2251	0,0348
	»	3090—3095	—	85	3,62	—	1,25	0,0650
				Babayurt				
Clays	N_1srm	489—499	—	10,2	2,22	—	0,1201	0,0328
	»	519—529	—	15,4	3,08	—	0,1860	0,0425
				Sulak				
Clays	Na_2k	773—780	—	7,9	2,18	—	0,0952	0,0322
	»	800—810	—	17,4	1,378	—	0,2095	0,0217
	»	951—961	—	11,9	1,783	—	0,1327	0,0411
	»	993—1003	—	12,4	4,672	—	0,1494	0,0690
	»	1012—1038	10,4	10,8	3,418	0,4360	0,1158	0,0506
	»	1100—1103	8	14	—	0,3355	0,1639	—
	N_1ak+mt	1108—1117	—	6,5	3,855	—	0,0734	0,0569
	»	1144—1152	1,3	11,1	2,167	0,0545	0,1330	0,032
				Karaman				
Clays	N_2	103—113	—	52	—	—	0,5400	—
	»	303—310	16	40	—	0,6338	0,4560	—
	»	600—614	31	—	—	1,3000	—	—
	N_2ap	804—816	21	54	—	0,8807	0,6512	—
	»	1103—1109	—	17	—	—	0,2050	—
	N_2ak	1402	26	37	—	1,0904	0,4462	—
	N_1mt	1919	24	15	—	1,2023	0,2161	—
	»	2100	—	17	—	—	0,2563	—
	»	2500	8	81	—	0,4475	0,3040	—
	N_1srm	2993—2996	10	60	—	0,5708	0,9849	—
	»	3002—3003	—	66	—	—	0,4422	—

Note: Commas indicate decimal points.

TABLE 16. RADIOACTIVITY OF SEDIMENTARY ROCKS OF DAGESTAN

Lithologic composition	Age	Content of Radioactive elements, %						Heat emission, 10^{-12} cal/cm^3·sec					
		U·10⁻⁴		Th·10⁻⁴		K		U		Th		K	
		min	max	min	max	min	max	min	max	min	max	min	max
Clays	N_2	8	31	6,5	54	1,38	4,67	0,3351	1,3000	0,0784	0,6512	0,0217	0,0690
	N_1tsch	14		9		4,63		0,783		0,145		0,091	
	Mz	13	45	5	39	1,44	1,99	0,7510	2,6000	0,0800	0,6280	0,277	0,0038
Argillites	Mz	8	37	1	12	0,34	1,13						
Sandstones	N_1tsch	27		5		0,785		1,305		0,0836		0,0150	
	Mz	3		10		0,72		0,168		0,161		0,0124	
Aleurolites	Mz	1	40	1	25	0,03	3,62	0,0510	2,2400	0,0230	0,4020	0,0006	0,00650
Limestones	Mz	3	33	4	36	0,79	1,68	0,1710	1,9300	0,0665	0,5790	0,0163	0,0343
		1	32	5	44	0,02	1,94	0,0570	1,8230	0,0830	0,7225	0,0004	0,0579

Note: Commas indicate decimal points.

TABLE 17. THERMAL EFFECT OF RADIOACTIVE DECAY IN THE PORTION OF THE PROFILE IN THE INVESTIGATED REGIONS OF DAGESTAN STUDIED /109

Depth interval investigated, in meters	Lithologic composition	Age	Thermal effect or radioactive decay, 10^{-12} cal/$cm^3 \cdot sec$	Potential increase in therm. flow due to radioactive decay in the given interval, 10^{-6} cal/$cm^2 \cdot sec$
		Yuzhno-Sukhokumskaya		
1,900-2,300	Clayey layer	Pg_2-N_1	0.414	0.0166
2,500-2,750	Limestones with clay interbedding	Cr_2	2.06	0.0515
3,100-3,200	Aleurolitic-arenaceous member	"	1.027	0.01
3,290-3,340	Arenaceous member with argillaceous interstratification	Cr_1	0.97	0.005
3,410-3,420	Argillaceous member	"	1.451	0.0014
3,420-3,464	Dolomitic member	J_3	0.759	0.0039
3,620-3,730	Layer of argillaceous sandstone	J_1	0.73	0.008
		Russkiy Khutor		
2,435-2,635	Limestones with interstratifications of calcareous clays	Cr_2-Cr_1	0.944	0.019
2,635-2,770	Sandy-aleurolitic member	Cr_1	0.504	0.0068
2,770-3,152	Clayey-aleurolitic member with interbedded sandstones	"	0.499	0.00758
3,152-3,220	Argillaceous aleurolites	"		
3,152-3,172	" "	"	1.134	0.00227
3,172-3,207	" "	"	1.27	0.0044
3,207-3,220	" "	"	1.672	0.00217
3,220-3,259	Interbedding of limestones, aleurolites, marls	"	0.834	0.00175
3,259-3,280	Interbedding of clays & dolomitized sandstones	"	0.814	0.0017
3,280-3,310	Dolomites	Cz_1		
3,280-3,305	"	"	0.75	0.0019
3,305-3,310	"	"	0.520	0.00011
3,310-3,382	Alternating clays & sandstones	Cr_1-J_2	1.358	0.00978
3,382-3,395	Aleurolites	J_2	1.74	0.00978
3,534-3,538	Clays	J_1^2	1.923	0.00226

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TABLE 17. (Continued)

Depth interval investigated, in meters	Lithologic composition	Age	Thermal effect or radioactive decay, 10^{-12} cal/ $cm^3 \cdot sec$	Potential increase in therm. flow due to radioactive decay in the given interval, 10^{-6} cal/$cm^2 \cdot sec$
		Solonchakovaya		
2,600-2,950	Limestones alternating with carbonaceous clays	Cr_2	0.438	0.0153
3,422-3,444	Aleurolites	Cr_1	0.761	0.00167
3,444-3,530	Interbedding of limestones with sandstones	"	0.841	0.0072
3,530-3,622	Interbedding of dolomites with argillites	"	0.857	0.00788
3,680-3,735	Aleuritic argillites	J_3	2.164	0.0119
		Bazhigan		
3,513-3,553	Interbedding of sandstones and aleurolites	J_2	0.193	0.0008
3,553-3,637	Interbedding of limestones and sandstones	"	0.2703	0.0023
3,713-3,852	Interbedding of sandstones, aleurolites, and argillites	J_1	0.568	0.0079
		Stepnaya		
2,600-2,950	Limestones alternating with carbonaceous clays	Cr_2	4.159	0.0406
3,328-3,440	Argillaceous layer	Cr_1	2.695	0.0302
		Vostochno-Sukhokumskaya		/111
2,725-2,845	Limestones with interstratifications	Cr_2	0.928	0.0116
2,845-2,905	Calcareous sandstones	"	0.879	0.0053
		Makhachkala (Well No. 215)		
1,500-1,600	Aquiferous sandstones	N_1 tch	1.2906	0.0129
1,600-1,700	Clays with interbedded marls	"	1.0190	0.0102
1,700-1,800			0.4038	0.0040

TABLE 17. (Concluded)

Depth interval investigated, in meters	Lithologic composition	Age	Thermal effect or radioactive decay, 10^{-12} cal/ $cm^3 \cdot sec$	Potential increase in therm. flow due to radioactive decay in the given interval, 10^{-6} $cal/cm^2 \cdot sec$
		Gasha		
2,100-2,900	Argillaceous fine grained limestones	Cr_2	0.1178	0.0178
1,900-3,000	" "	"	0.2599	0.0037
3,000-3,100	" "	Cr_2-Cr_1	1.3150	0.0132
3,100-3,200	" "	Cr_1	0.3840	0.0035
		Babayurt		
400-500	Argillaceous member	N_1 srm	0.1906	0.0019
		Sulak		
700-800	Sandy clay	N_2 ak	0.127	0.00127
800-900	" "	"	0.2300	0.0023
900-1,000	" "	"	0.2000	0.0020
1,000-1,100	" "	"	0.5100	0.0051
1,100-1,200	" "	"	0.3900	0.0039
		Karaman		
100-300	Calcareous gray clay	Q_1	0.54	0.0108
300-600	" " "	N_2apsh	1.89	0.0327
600-1,100	" " "	"		0.0682
1,100-1,300	" " "	N_2 ak		0.0062
1,300-1,400	" " "	"		0.0154
1,400-1,900	" " "	N_2 ak + N_1 mt		0.0709
1,900-2,100	" " "	N_1 mt		0.0051
2,100-2,900	Slightly arenaceous, micaceous clay	N_1 srm		0.1244
2,900-3,000	" "	"		0.0044

By and large the total emission of radiogenic heat in the sedimentary layer proved to be very significant (Table 19). In the Russkiy Khutor field, for example, the thermal effect from the decay of radioactive elements contained in an interval only of 1 km thick is equal approximately to 5% of the observed conductive thermal flow, and in the Karaman field it is even 10%. Considering that the sedimentary sheath over that portion of the skif platform studied is almost 4 km thick, it can be concluded that the total rate of radiogenic heat generation in it is about 20% of the observed thermal flow. As far as concerns the Tersk-Kaspiysk forward depression, here the distribution of the radioactive elements was studied only in the upper profile (Quarternary and Neogenic formations) and the extension of these evaluations (possibly maximum because of the abundance of clayey varieties) to the lower intervals is invalid. /113

TABLE 18. RESULTS OF EVALUATION OF THE RADIOGENIC THERMAL EFFECT IN THE SEDIMENTARY LAYER OF DAGESTAN

Field investigated	Interval investigated, in meters	Age	Potential increment in thermal flow from radioactive decay, 10^{-6} μcal/cm²·sec	
			Total for all intervals investigated	Average for each 100 m of the investigated interval
Gasha	2,100-3,200	Cr_2-Cr_1	0.033	0.0035
Makhachkala	1,500-1,800	N_1 tch	0.024	0.0080
Karaman	100-3,000	Q+Tr N_2	0.339	0.0116
Babayurt	400-500	N_2 apsh	0.0019	0.0019
Sulak	700-1,200	N_1 mt; N_2apt ak	0.0144	0.0029
Russkiy Khutor	2,435-3,395	Cr_2-J_2	0.0597	0.0060
Yuzhno-Sukhokumskaya	1,900-2,300	Pg_2-N_1	0.0166	0.0042
	2,500-3,630	Cr_2-J_2	0.798	0.0065
Solonchakovaya	2,600-2,950	Cr_2	0.0153	0.0043
	3,422-3,730	Cr_1-J_2	0.0286	0.0090
Stepnaya	2,600-2,955	Cr_2	0.0400	0.0114
	3,328-3,440	Cr_1	0.0300	0.0230
Vostochno-Sukhokumskaya	2,725-2,905	Cr_2	0.0169	0.0090
Bazhigan	3,513-3,852	J_3-J_2	0.0110	0.0030

Attention should be called to the fact that the evaluations obtained for the role of radiogenic heat in the formation of the conductive thermal flow are of relative nature, strictly correlating only to the given concrete period of the investigated region's geological history. When making paleo- /116 reconstructions and other extrapolations in time, it is necessary to keep in mind the decrease in the content of radioactive elements in proportion to their decay and the corresponding reduction in the thermal capacity of the latter.

The values actually observed at the various levels within the sedimentary cover for the conductive thermal flow turn out to be less than is indicated by the calculations taking into consideration the contribution of heat emitted by the dispersed radioactive sources (Table 19). This non-correspondence may be the result of a lateral heat hrain (for example, as the result of movement of the underground water absorbing it) or of the occurrence of energy-consuming processes deep in the interior. This is most clearly manifested in the Karaman field where the thermal flow would have to be increased by 0.34 $\mu cal/cm^2 \cdot sec$ in the 100-3,000 m interval as a result of the emission of radiogenic heat (from 0.99 $\mu cal/cm^2 \cdot sec$ observed at the 3,000 m level to 1.33 at 100 m), but instead it is reduced in that interval to 0.68 $\mu cal/cm^2 \cdot sec$. Correlation of these data leads to the conclusion that energy-consuming processes are taking place in the sedimentary layer of the Karaman region, the capacity of which exceeds the effect of radioactive decay by almost two times.

TABLE 19. CHARACTERISTICS OF THE THERMAL REGIMEN IN THREE FIELDS /114

Depth or investigated interval, in meters	Therm. flow, 10^{-6} cal/cm^2·sec: Observed	Therm. flow, 10^{-6} cal/cm^2·sec: Calculated with consideration of thermal effect of radioactive decay by the formula* $q_x = q_H = \Delta q$	Geothermal gradient computed from calculated values of thermal flow by the equation** $\mathrm{grad}\ T = \frac{q_x}{\lambda}$, °C/m	Temperature, °C: Observed (T_H)	Temperature, °C: Computed from calculated values of thermal flow by the equation*** $T_x = T_H - \int_x^H \mathrm{grad}\ T dx$
			Russkiy Khutor		
2,435	1.19	1.45	0.04	104.6	104.4
2,635	1.76	1.43	0.024	111.2	113.8
2,770	1.16	1.42	0.027	116.12	117.71
3,152	--	1.41	0.027	125.9	131.08
3,172	1.02	1.41	0.027	126.5	131.78
3,207	1.38	1.41	0.026	127.2	133
3,220	--	1.41	0.026	127.5	133.42
3,259	0.96	1.41	0.026	--	--
3,280	--	1.40	0.026	128.5	135.4
3,310-3,382	1.39	1.39	0.026	--	135.73
			Yuzhno-Sukhokumskaya		
1,900-2,300	1.32	1.45	0.038		
2,500-2,750	1.285	1.43	0.024	111 (2,500 m)	117.8 (2,500 m)
3,100-3,200	1.21	1.377	0.026	130 (3,100 m)	123.8 (2,750 m)
3,290-3,340	1.22	1.367	0.026		140.44 (2,890 m)
3,410-3,420	0.86	1.362	0.036		147.51 (3,464 m)
3,420-3,464	1.52	1.361	0.020		
3,570-3,620	0.74				
3,620-3,730	1.35	1.358	0.023		142.94 (3,700 m)
3,730	--	1.35	--	140 (3,600 m)	

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TABLE 19. (Continued)

Depth or investigated interval, in meters	Therm. flow, 10^{-6} cal/cm^2·sec		Geothermal gradient computed from calculated values of thermal flow by the equation** grad T = $\frac{q_x}{\lambda}$, °C/m	Temperature, °C	
	Observed	Calculated with consideration of thermal effect of radioactive decay by the formula* $q_x = q_H = \Delta q$		Observed (T_H)	Computed from calculated values of thermal flow by the equation*** $T_x = T_H - \int_x^H \text{grad } T dx$
			Karaman		
100-300	0.60	1.33	0.052	20.95	15
300-600	0.57	1.32	0.044	25.98	25.4
600-1,100	0.73	1.28	0.036	32.4	38.6
1,100-1,300	--	1.22	0.030	45.34	56.6
1,300-1,400	--	1.21	0.030	50.4	62.6
1,400-1,900	0.99	1.19	0.032	52.1	65.6
1,900-2,100	0.98	1.12	0.030	63.96	81.6
2,100-2,900	0.82	1.12	0.030	70.05	87.6
2,900-3,000	0.99	0.99	--	91.55	111.6

* q_x, calculated thermal flow; q_H, conductive thermal flow through the underside of a layer of thickness x; Δq, thermal effect of the radioactive decay in the layer (H - x).

** grad T, temperature gradient in the layer (H - x).

*** T_x, temperature at a given depth x; T_H, temperature at the bottom of the layer (H - x), i.e., at the depth H.

Conclusions

1. The thermal conductivity of the various types of rocks comprising the sedimentary sheath of Dagestan was investigated in 125 test samples. It was established that: /117

a) the sandstones have the highest thermal conductivity (up to 8.9 mcal/cm·sec·°C), and the clays have the lowest (up to 1.5 mcal/cm·sec·°C);

b) the coefficient of thermal conductivity for the same type rock increases with an increase in the depth of the deposit, which is related to the compression of the rock and is not dependent on its age;

c) the magnitude of the correction in the coefficient of thermal conductivity under natural conditions in comparison with laboratory conditions under the influence of moisture reaches 10-15% for the clays and 30% for the sandstones.

2. Values were determined for the conductive thermal flow in 12 exploratory fields in Dagestan: Gasha (0.87 μcal/cm^2·sec), Izberbash (0.74 μcal/cm^2·sec), Kaspiysk (1.05 μcal/cm^2·sec), Makhachkala (0.96 μcal/cm^2·sec), Russkiy Khutor (1.32 μcal/cm^2·sec), Yuzhno-Sukhokumskaya (1.25 μcal/cm^2·sec), Solonchakovaya (1.03 μcal/cm^2·sec), Stepnaya (1.32 μcal/cm^2·sec), Bazhigan (1.58 μcal/cm^2·sec), Karaman (0.96 μcal/cm^2·sec), Sulak (0.65 μcal/cm^2·sec), and Babayurt (0.70 μcal/cm^2·sec).

3. The differentiation of the conductive thermal flow was established in the different geologic-tectonic zones of Dagestan. In the region of Paleozoic folding (Skif platform) the average thermal flow amounts to 1.30 μcal/cm^2·sec; in the region of Cenozoic folding (Tersk-Kaspiysk forward depression) it is 0.85 μcal/cm^2·sec.

4. The content of long-lived radioactive isotopes was determined experimentally in 160 samples of the various sedimentary rocks of Dagestan. The /118
highest content of isotopes is in the clays, and the limestones have the lowest content. The high radioactivity of the Mesozoic rocks of the Dagestan Plain (Russkiy Khutor, Δq_{rad} = 0.0060 μcal/cm^2·sec per 100 m) in comparison with the Piedmont (Gasha, Δq_{rad} = 0.0035 μcal/cm^2·sec per 100 m) is striking,

although no unambiguous laws of distribution were established for the distribution of the radioactive elements according to field and in the profile.

5. The thermal effect of the decay of long-lived radioactive isotopes in the sedimentary layer of Dagestan was determined quantitatively. The generation of radiogenic heat in the sedimentary layer of Dagestan amounts to not less than 20% of the total amount of the conductive thermal flow.

6. The results of these investigations can be utilized for a more detailed description of the thermal regimen in the depths of the Dagestan petroleum-gas fields, and for evaluation of their thermal energy resources for the purpose of practical utilization. These data are also an essential part in forming an overall picture of the distribution of the deep thermal flow in the Dagestan territory.

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